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Choir acoustics – an overview of scientific research published to date

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Abstract

Choir acoustics is but one facet of choir-related research, yet it is one of the most tangible. Several aspects of sound can be measured objectively, and such results can be related to known properties of voices, rooms, ears and musical scores. What follows is essentially an update of the literature overview in my Ph.D. dissertation from 1989 of empirical investigations known to me that deal specifically with the acoustics of choirs, vocal groups, or choir singers. This compilation of sources is no doubt incomplete in certain respects; nevertheless, it will hopefully prove to be useful for researchers and others interested in choir acoustics.

General papers

Sacerdote (1957) studied some aspects of solo singing, but also briefly mentioned the F_0 behavior of a quartet of sopranos, apparently consisting of students who did not quite qualify as soloists. He suggested the use of the autocorrelation function for measuring the dispersion in F_0 . He found the latter to be 130 cents when the group sang in unison. This very large value seems to indicate that the singers were using a large vibrato.

Choral intonation of intervals

The first modern paper on sounds of entire choirs appears to be one of Lottermoser & Meyer (1960). They used commercial recordings of three reputable choirs to study the intonation of simultaneous intervals. They found that the choirs tended to make major thirds rather wide, with an average of 416 cents, and minor thirds quite narrow, with an average of 276 cents. The authors suggested that this served to increase the contrast between the major and minor tonality of chords. Octaves and especially fifths were sung very close to just intonation. The dispersion in fundamental frequency, measured as the bandwidth of partial tones, was also investigated. The average of this dispersion measure varied greatly, from 2 to 60 cents, but was typically in the range 20-30 cents. It should be noted that with this method, it is not possible to discriminate between the frequency dispersion that results from small voice instabilities or vibrato and the dispersion caused by intonation disagreement amongst the singers.

Barbershop intonation

Hagerman & Sundberg (1980) studied the intonation of barbershop quartets. They found that the accuracy in phonation frequency was very high, and practically independent of vowel. Intervals with many common partials were found to be more accurately intoned than those with few common partials. The exact size of most intervals deviated systematically from the values stipulated in both just and Pythagorean intonation. The deviations were found not to give rise to beats. The proposed explanation for this was the finite degree of periodicity of tones produced by the singers.

Acoustic preferences of a small ensemble

Marshall & Meyer (1985) had a quartet sing in an hemi-anechoic room, i.e., a room with structural reflections from the floor only. The rest of the room acoustics was synthesized, systematically varied and played to the singers over loudspeakers. The effect of the early reflections was studied (Marshall *et al*, 1978) having found previously that these are of great importance to ensemble playing. The singers were asked to rate the difficulty of singing in the various reverberation fields. Rather than the early reflections, the loudness of the reverberation appeared to be the most important to the choir singers. The reverberation time, however, was found to be of little significance. Lateral early reflections were more appreciated than vertical ones, especially if the level of the late reflections was high. Irrespective of the reverberation time, the singers preferred early reflections in the time range 15-35 milliseconds, corresponding to reflecting walls at distances of 2.6-6 meters. Early reflections arriving with 40 ms delay (6.5 m) were particularly disliked. The kind of music used was not described. Similar but less consistent results were obtained with a larger ensemble. The main contribution of this paper was, however, a very detailed charting of

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the directivity of male singer voices, as a function of frequency.

The Lombard effect in choir singers was studied by Tonkinson (1990). The Lombard effect is the tendency to raise one's voice in the presence of other loud sounds. He found that while the Lombard effect can occur in inexperienced and experienced singers alike when they are exposed to choir-like conditions, they can learn to resist it if given appropriate instruction.

The dynamic ranges of choir singers was measured by Coleman (1994). He recorded singers individually and found ranges from 11 dB to 33 dB SPL. Most of the difference was manifest in the ability of the more trained singers to sing more softly. The difference in maximum SPL between trained and untrained singers was not large in this study.

Choral spacing was the subject of a major study on singer and auditor preferences by Daugherty (1996). A choir was asked to sing the same excerpt of music in systematically varied formations. Immediately afterwards, the choir singers filled in a questionnaire. The 160 auditors made paired comparisons of high-fidelity stereo recordings taken in an audience position in the auditorium. The experiment was very well-controlled, with great attention to detail. For example, a video-taped conductor was used so as to minimize irrelevant variation between trials. From Daugherty's results, we note that choir singers preferred a wider spacing to the normal spacing, and that this preference was stronger than that for mixed formation over sectional formation. The auditors showed some preference for the choral sound produced in wider spacing.

These results were confirmed in a second study (Daugherty, 2001). Here the singers were asked to comment also on the amount of tension and stress perceived in the three types of choir formation. Less tension was reported in spread formations. Interestingly, no significant preference was observed for controlled singer placement as devised by the conductor, compared to a random block sectional formation. Trials made with all-male and all-female ensembles showed that the singers in the female ensemble preferred the greatest spacing to the intermediate spacing, while the singers in the male ensemble preferred the intermediate spacing. The reason for this is not determined.

From Daugherty's work it seems clear that, on the whole, singers and auditors alike prefer **more spacing** than is common in conventional formations, especially when risers are used. This appears to agree with other findings made using acoustic measurements (below).

Jers (1998) demonstrated the feasibility, if laborious, of simulating the sound of an entire choir on stage in a concert hall, in his case for the purposes of optimizing numerical simulations of room acoustics for multiple sound sources. This large work included (a) the construction of an artificial singer, being a mannequin containing high fidelity loudspeakers with a total radiation characteristic that was very close to that of a real singer; (b) the recording of a live 16-person choir with separate channels for each voice, (c) the playback of one voice at a time through the mannequin, which was moved from one singer position to another and the signals later mixed to re-assemble the choir sound, (d) the same but with the room acoustics simulated by numerical convolution with the room impulse responses, (e) listening tests, assessing to what extent the separate singer sources could be merged, in order to reduce the computational load. The work also gives very detailed directivity data on the voice of one soprano singer.

The perception of **child chorister voices** has recently been studied by Howard, Szymanski and Welch (2000, and forthcoming). An experiment was designed to establish whether or not listeners can tell the difference between trained girl and boy English cathedral choristers that are singing the top lines in samples of professionally recorded sacred choral music from one cathedral choir. Material was taken from two CD recordings of Wells cathedral choir, one with girls and the other with boys singing the top line (soprano part). In the experiment, the lower three parts (alto, tenor and bass), the musical director and the acoustic environment remained constant. However, the musical material itself was different, in keeping with commercial needs. A listening test was created consisting of 20 excerpts each lasting 20 seconds, where 10 tracks were of girls singing the top line and 10 of boys. The results from 189 listeners suggested that listeners can identify the sex of the choristers singing the top line with an average accuracy of approximately 60%, but also that the musical context plays an important factor in this perceptual ability. In addition, boy voices were accurately identified more often than girl voices, and adult listeners performed this task more reliably than did child listeners.

Additionally, there is a handful of Ph.D. dissertations concerning various aspects of choral sound from music departments at U.S. universities. Unfortunately the acoustic and/or methodological background for some of these appears to be weak, which can make the conclusions typically unsurprising or poorly corroborated. For completeness, all works known to me will be listed here.

Hunt (1970) made recordings of three vowels sung by school choirs of three age categories and had an expert jury rate the vocal blend and the vowel intelligibility as "good", "acceptable" or "poor". The subjective ratings were compared to spectrograms and a correlation between them was sought. Hunt reported finding that the samples rated as "good" typically had spectral distributions in which "all the sound was concentrated into frequency bands which were exactly aligned with the harmonic series." In other words, the jury may have been rating simply the accuracy of intonation. Hunt concluded that unity of vowel sound is essential in achievement of good vocal blend, and proposed that "the problem of unity of vowel is one of intonation of formant frequencies." Since vowel identity is defined by the location of the formant frequencies, this is quite uncontroversial.

Tocheff (1990) had five judges assess 32 trial performances of two live but visually screened choirs, whose formations were changed for (1) (un-)controlled placement of singers, (2) sectional or mixed, and (3) polyphonic or homophonic texture. For each trial, the judges rated six variables related to the quality of choral sound. The results showed preference for controlled placement over uncontrolled, and for sectional formation over mixed. Some difficulties with this arrangement would be for the judges to maintain stable criteria for six variables over 32 performances, and for the trials to be truly blind.

Ford (1999) asked 139 undergraduate students to listen to two choral excerpts, one performed in a soloistic mode with a resonant singer's formant, and the other in a more normal choral mode of singing. The overwhelming majority of listeners preferred the choral mode, especially if they had some choral training. However, the four-part choir that produced the stimulus sounds contained only eight singers, presumably two to each part. This might yet have worked, had the stimulus sounds been recorded in a very reverberant room; but the recording was made in an anechoic chamber, which calls into question whether the ensemble sound could really be called choral.

Giardiniere (1991) and Eckholm (2000) asked auditors to rate rather subtle aspects of recordings of choir sounds, but there was no control of the sound reproduction quality, nor of how the sounds were presented; the tapes were simply mailed to the auditors. This makes it difficult to draw valid conclusions.

The KTH research track (from 1983)

The first account of a continuing research effort in choir acoustics is this author's PhD thesis from 1989. As is common in Sweden, this thesis was composed of reprints of six recent research papers, held together by a framework chapter. Four of these appeared in reviewed archive journals while two were published only in the progress report TMH-QPSR of the author's department. A concise overview of this thesis is given in Ternström (1991). An adapted version of the thesis abstract follows.

Three different kinds of experiments are reported: (1) the control of F_0 and the vowel articulation of singers were investigated in the laboratory, by having individual choir singers perform vocal tasks on demand or in response to auditory stimuli; (2) typical values of sound levels, F_0 scatter and long-time averaged spectra were obtained by measurements in normal or close-to-normal conditions; and (3) models for certain aspects of choral sound were formulated and evaluated by synthesis.

In performance, the choir singer refers to two acoustic signals: the own voice, or *Self*, and the rest of the choir, or *Other*. Intonation errors were found by Ternström & Sundberg (1988) to be induced or increased (a) by large differences in sound level between *Self* and *Other*, (b) by unfavourable spectral properties of *Other*, and (c) by articulatory manoeuvres, i.e., by so-called intrinsic pitch (Ternström, Sundberg & Colldén, 1988). The magnitude of the errors would be indirectly related to room acoustics (a,b) and to voice usage and textual content (b,c). When singing alone, singers from one choir used a vowel articulation that was different from that in speech and also more unified; it was also in some respects different from solo singing (Ternström & Sundberg, 1989).

Might **the room acoustics affect the voice usage** of choir singers? This issue was investigated using the long-time average spectrum (LTAS), measured in three rooms × three choirs × three dynamic levels × two musical selections. A calibrated reference noise source was used to account for the influence of the room acoustics on the sound transmission from choir to listener. Long-time average spectrum effects of room acoustics and musical dynamics were large, as expected; those of choir and musical material were smaller. In other words, the average spectral distribution of the choral sound was influenced more by room acoustics and musical nuance than by choir identity or the music that was sung. To some extent, the three choirs studied adapted their sound level and voice usage to the room acoustics in the three different locations (Ternström, 1993a).

Small random fluctuations in F_0, called flutter and wow, are always present in human voices. By flutter I mean small variations (on the order of 20 cents or less) in F_0 that are too rapid to be perceived as a modulation of pitch, i.e. faster than about 5 times per second. Wow, on the other hand, refers to a drift in F_0 that is slow enough to be perceived as a pitch change. With multiple voices, flutter and wow cause, through interference, an essentially random and independent amplitude modulation of partial tones, which is known to cue the perceptual "chorus effect". In other words, the beating between many singers, who cannot be exactly in unison at all instants, is so complex and variable as to be for all practical purposes random. The chorus effect is also affected by the reverberation properties of the room. Choral sounds were explored by means of synthesis, and the importance of realistic flutter was established. Flutter in choir singers was analysed, and simulated in single synthesized voices. Expert listeners were unable to discriminate between simulated and authentic flutter (Ternström & Friberg, 1989).

Experiences gained in the above work were also combined with work in music performance by rule in a realisation of the Monteverdi *Vespers* (Ternström, Friberg & Sundberg, 1988).

After Ternström's dissertation in 1989, work in choir acoustics at KTH has continued, albeit at a somewhat reduced rate.

Scatter in pitch within a section, preferred and tolerated

Ternström (1993b) investigated the issue of how much out-of-tune the singers in a section can be, and still sound acceptable. Ten listeners with extensive conductor and/or singer experience could select sounds from an inventory of stimulus sounds, with synthesized stereophonic voice ensembles "singing" various sustained vowels in unison. The results showed that most listeners would *tolerate* a standard deviation in F_0 of 14 cents, meaning that two-thirds of the ensemble would be within ±14 cents of each other. When asked for their *preference*, however, most listeners opted for a zero level of pitch scatter. The preferences depended somewhat on both the vowel ([u] [a] [æ]) and on the voice category (S, A, T, B) of the stimulus.

Scatter in voice types (vocal tract lengths)

In the same investigation, similar data was collected for scatter in formant frequencies. When the lower formant frequencies F1 and F2 were spread out across the ensemble, corresponding to an increased divergence in vowel pronunciation, surprisingly little effect was audible, and this factor was therefore not included in the experiment. When the higher formant frequencies F3-F5 were spread out, corresponding to an increased spread in singer voice types, the perceptual difference was more salient, although the ratings were not as clear-cut as in the intonation part of the experiment.

The Self-to-Other ratio (SOR)

The most recent papers from KTH deal with the issue of hearing one's own voice inside the choir. We state again that *Self* denotes the sound of one's own voice, while *Other* denotes the sound of the rest of the choir, including the sound reverberated by the room. Each of these two components has a sound level (at the singer's ears) that can be expressed in decibels. The *Self* component has an airborne part and a bone-conducted part. These two parts contribute in varying measure to the level of the total sound that one perceives of one's own voice (Pörschmann, 2000), but the airborne sound usually dominates. The *Other* component can be divided into direct sound, which arrives straight from the other singers, and reverberated sound, which has been reflected many times in the room.

The Self-to-Other ratio then becomes the difference in decibels between the sound levels of *Self* and *Other*, as experienced by a given singer. If the SOR is positive, *Self* is heard as louder than *Other*; and this is most often the case. The singer must hear enough of his or her own voice, or vocal control will suffer. The question is, how much is enough? How large is the SOR in normal situations, and how large would the singers prefer it to be?

There are two major acoustic factors that govern the SOR, and both operate by changing the level of *Other*. (For a given voice effort level, the level of *Self* is rather constant and can be manipulated only slightly, e.g., by using reflectors close to oneself.) The first is the **spacing** between singers, which governs the level of the direct part of *Other*. The other is the amount of **reverberation** in the room, which governs the reverberated part of *Other*. The choral director can control both of these factors, to some extent.

Typical SOR values in normal conditions

Ternström first developed a method for measuring the SOR (1994) and then used this to measure typical SOR values in various positions in two choirs (1995). The SOR was found to vary between approximately +1 dB and +8 dB, with low values being more common near the centre of the choir (more neighbours) and higher values being more common near the ends (fewer neighbours). The average SOR was +3 dB in one case (choir of 32 singers in two rows on stage in a large recording theater) and +4 dB in the other (choir of 20 singers in one row in a congregational hall).

Preferred SOR

The question remained whether these values are near the optimum, or whether the singers would prefer a different SOR if they had a choice. This might be the case, since artists who perform with adjustable amplification often are very particular about the exact amount of self-monitoring they require. Ternström (1999) had 23 experienced choir singers adjust the SOR to their preference, relative to a synthesized ensemble, in various conditions of vowel, F_0 and unison/chord. There were two main interesting findings. The first was that choir singers are indeed quite particular about SOR, in the sense that they reproduced their individual preferences with great accuracy. The second was that the singer preferences were highly individual, ranging from +1 dB to nearly +15 dB. The average preferred SOR was, however, +6dB, which is a significantly higher value than the 3-4 dB found in typical conditions.

Simulating the ensemble effect

In music technology, a sought-after device is one that would convert the sound of a single voice into a unison section of singers. Kahlin & Ternström (1999) investigated various signal-processing techniques for accomplishing this in the frequency domain. They demonstrated that the chorus or ensemble effect is analytically elusive because the modulation by beating becomes very rapid at the high end of the spectrum. Nevertheless, it proved possible to build a basic chorus-converter with modest sound quality using a filter bank or vocoder approach with amplitude-modulated outputs.

Other literature

The literature yield increases considerably if the scope is widened to include work that is not directly concerned with choir singing, but rather with relevant aspects of voice production, room and ensemble acoustics, and perception. A few prominent examples will be mentioned.

Differences between solo and choir singing

Several workers have reported on measurable differences in voice production between solo and choir singing.

Harper (1967) performed extensive spectrographic and aural comparisons of selected vowels sung at selected pitches. He found that there were no systematic differences in formants 1 and 2 between solo and choir mode; that there were [other] audible differences between solo and choir mode; but that no consistent pattern of change in the partial tone structure could be ascribed to these differences. He reported also that in choral mode, the partial tones *in between* formant regions were stronger in choral mode [my italics]. This seems odd and it would be interesting to see the printouts. Curiously, however, although spectrograms are discussed at length, not one is reproduced in the thesis. My interpretation is that the formant resonances may have been more pronounced in the solo mode.

Rossing *et al* (1986) examined several voice properties of eight baritones who were proficient in both choral and solo modes. The singers sang together with the recorded sound of the rest of the choir and a piano, respectively. The singers used more power in the region of the singer's formant (2-3 kHz) in solo mode, while the fundamental region had more power in choral mode. In choral mode, the singers adapted their sound level to that of the recorded choir, whereas in solo mode the level sung depended much less on the level of the piano accompaniment.

A similar study was performed a year later (Rossing *et al*, 1987), with five sopranos as subjects. There were no conclusive indications of a singer's formant, but the singers did produce more energy in the 2-4 kHz region in solo mode, even when allowing for the louder voice in this mode. However, they accomplished this in different ways. The vibrato extent was somewhat larger in solo mode.

Letowski *et al* (1988) studied the average spectra of 12 singers recorded in mono as an ensemble, in SATB sections, and solo. They were also recorded when singing alone, with the ensemble or the rest of their own section played back over headphones. A validation experiment was first performed to verify that the sound produced by a section of five was perceived to be the same as the sound of a singer recorded in isolation, mixed together with the recording of the rest of that section. The singers also stated that they were comfortable with the procedure. The authors concluded that (a) there were several significant spectral differences between solo and choral mode, particularly for the four males with vocal training; (b) the vocally untrained singers tended to 'perk up' [my description] to a brighter voice when singing with the ensemble, whereas the trained singers 'held back' when attempting to blend with the ensemble. The article gave no definition of training, but, as it happened, the female singers were considered untrained while most of the male singers were trained, so this may be a confounding factor. In a listening test, expert listeners also rated the recordings of the individual voices on a 'pleasantness' scale. High ratings were achieved by those singers who adapted considerably between solo and choral mode.

On the whole, it seems clear that the tasks of solo singers (to be clearly heard) and choir singers (to contribute but blend) are acoustically quite different, and usually require different modes of voice production. This does not imply that the two activities cannot be combined; but rather that student singers and their teachers need to be aware of the differences during training.

Intonation of major thirds

Nordmark & Ternström (1996) studied the preferences for intonation of the major third in ensemble sounds, in which the presence of beats cannot serve as an auditory cue for errors in pure intonation. This would include choirs and string sections of orchestras. Sixteen subjects with ensemble experience adjusted the major third interval in synthesized dyads to their preference. The average preferred major third was 395.4 cents (±7 cents), which may be compared to 400 cents of equal temperament or to 386 cents of pure intonation. This means that there was no preference for pure intonation. The preferences averaged by subject ranged from 388 cents to 407 cents.

Other choir-related topics

Sundberg (1987) provides a thorough account of the acoustics of **the production of the singing voice**. Howell (1985) discussed the **auditory feedback of singers**. Very detailed information on the relative importance of airborne and bone-conducted feedback was recently published by Pörschmann (2000), building on groundwork by several others (Letowski & Caravella, 1994; Tonndorf, 1972; von Békésy, 1949). Marshall & Meyer (1985) reported on the **directivity of singers' voices**, which is relevant to choir formations and stage design. Dolson (1983), working mostly with violin sounds, investigated the perceptual cues that are necessary to identify **ensemble sounds** as such. McAdams (1984) took a complementary approach, in studying the cues necessary for **perceptual fusion and parsing of complex sounds**. **Ensemble aspects of room acoustics** have been investigated by Gade (1982), for example, who looked at the subjective importance of early and late reflections; and by Plomp (1977), who described how the room acoustics can influence the sound level difference between "self" and "others". Naylor (1987) introduced a formal definition of "hearing-of-others" and "hearing-of-self", and suggested the use of the Modulation Transfer Index for measuring them. Some interesting, while not alarming, data on **hearing loss** that might be ascribed to professional choir singing was published by Steurer *et al* (1998).

Finally, a compilation of choir acoustics topics with regard to their possible relevance to choral practise can be found in Ternström and Karna (2002).

Conclusion

A condensed overview such as this cannot do justice to the work of the many dedicated researchers. The interested reader is encouraged to take part of many interesting observations that are made in the actual papers, and to form his or her own opinion of the ramifications of the results.

Of course, all this research notwithstanding, many interesting topics remain open for investigations in choir acoustics. Some examples are:

- To what extent does "shadowing" occur in choir singing, that is, the phenomenon that a few leading singers can seem to "carry" an entire section of others with them? How does this work?
- Many choir directors contend that, if a piece tends to go flat, it can help to sing it a semitone higher. Is this true, and if so, why?
- What are the acoustic principles, if any, that (should) contribute to the preferred placement of individual singers within a choir?

- What are the acoustic or perceptual differences between the sounds of choirs as compared to a cappella close harmony groups, with one voice to a part? Does it matter?

Glossary

For the benefit of readers with a predominantly musical background, some terms mentioned above are explained here.

autocorrelation function: a mathematical tool for describing how similar some segment of a sequence (here: a sound) is to a delayed segment of the same sequence. A sequence that repeats identically receives the maximum autocorrelation value when the delay equals the length of the repeated segment.

bandwidth: the frequency range or content of a signal. The sound on normal telephone links, for example, is restricted to frequencies from 300 Hz to 3400 Hz, and thus has a bandwidth of 3100 Hz.

cent: one-hundredth of a semitone

common partials: those partial tones of two sounds that coincide in frequency when the two sounds are playing a harmonic dyad. For example, in a pure fifth, every second partial of the upper tone will coincide with every third partial of the lower tone.

fundamental frequency, F_0: the frequency with which the vocal folds repeat their oscillatory motion in phonation. "The fundamental" is another name for the first (lowest) partial tone, whose frequency corresponds to the periodicity of the sound (cycles per second).

Modulation Transfer Index: a measure used in room acoustics that predicts how well the variations in the loudness of a source are transmitted to a listener. In rooms with little reverberation, the loudness at the listener's position will faithfully track that of the source (MTI close to 1); while in rooms with much reverberation the loudness at the listener will be smeared to an almost constant level (MTI close to 0). The MTI value correlates rather well with the intelligibility of speech in a room.

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