Acoustics for Choral Singing

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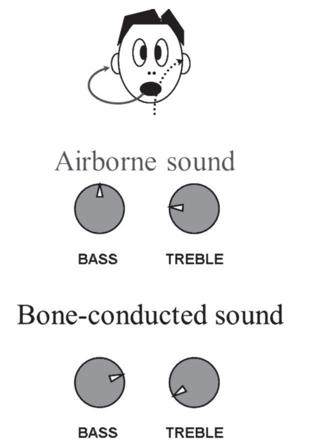
Every choir director has experienced how some rooms seem to be very easy for their choir to sing in, and sing well, while other rooms are more difficult. Similarly, some choir formations seem to work better than others in different circumstances. The reasons for these differences are often subtle and far from obvious. Here I will give an overview of the main acoustical factors, related to rooms and formations, that research has found to be important in particular aspect: that of hearing one's own voice in the choir, or not.

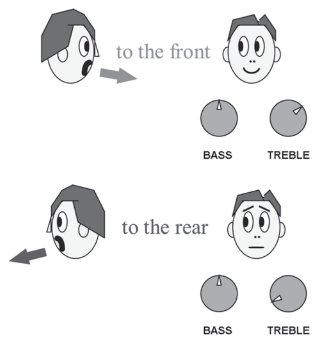
For accurate choral intonation, each singer must know exactly which pitch to sing in relation to the rest of the choir, and so it is important to hear the rest of the choir, herein called *Other*, with adequate balance between the sections. Also, each singer must be able to hear his or her own voice, herein called *Self*, in order to steer it. Clearly, also the accuracy in rhythm and pronunciation both require good perception of both Self and Other. Therefore it is useful to consider the acoustic mechanisms that regulate how well we as choir singers can hear both our own voice and the sound of the rest of the choir.

Hearing oneself

The first time you heard yourself talk on a recording, it sounded unfamiliar, thin and not like you at all. But others listening to the same recording all insisted that it was true to life. The reason, of course, is that, of all the ears in the world, only two are on *your* head. This gives your ears a unique perspective on your own voice. As you speak or sing, sound propagates from your voice to your ears along two separate paths: the *air-borne sound*, and the *bone-conducted sound*.

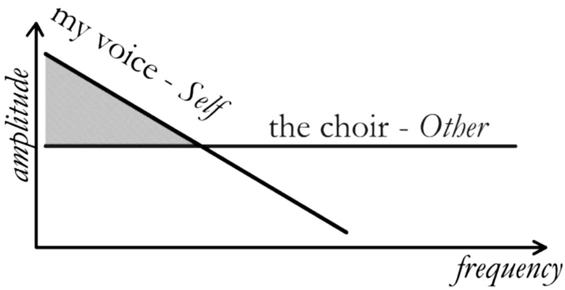


The sound of one's own voice loses treble along both paths.



The directivity of the voice is negligible at bass frequencies, but important in the treble range.

The airborne sound is that which comes out of your mouth. The high-frequency sounds, such as the higher overtones and sibilants, have short wavelengths in the air, and tend to travel straight ahead, hopefully toward the audience. The lower frequencies, with wavelengths longer than about the size of your head, diffract around your cheeks, and more of them will reach your ears. This frequency-dependent *directivity* of the voice means that you will hear your own airborne sound with less treble than do the audience and your neighbours in the choir. As for the bone-conducted sound, this is the buzzing of the vocal folds being transmitted through your skeleton up to the middle ears. This path loses even more of the high frequencies, much in the same way as when you hear mostly the annoying bass sounds from your neighbour's late-night disco. So, one's own voice has the bass turned up, and the treble turned down. For the choir singer, this timbral difference is probably fortunate! Even if there is some imbalance in strength between Self and Other, there will probably be some low-frequency part of Self that dominates over Other, most of the time. This is shown schematically by the gray area in the figure below.



A simplified representation of the relative timbre of Self and Other

It has been found (Pörschmann, 2000) that the air-borne and the bone-conducted sounds are about equally loud, in speech, but no-one has yet reported measurements of this balance for singing.

The balance of air-borne to bone-conducted sound depends also on which vowel one is singing. You can easily try this for yourself: first sing the vowels in food (/u/) and far (/a/)with the same vocal effort. The /a/ will be a lot louder in the air, simply because the mouth is more open. When we listen to voices, we expect this to happen, and so we tend to disregard such level differences. Now block your ears with your fingers, and repeat the same thing. You will find the opposite: that the /u/ is a lot louder than the /a/, because less of the acoustic energy is being sent out into the air, and instead gets conducted to your ears via the bones.

The relative strengths of the individual voices in the choir obviously will affect how well each hears their own voice. Naturally, if you and only you sing louder, your Self sound will increase. But if you sing louder, that might make your voice stand out above the rest; ideally all singers' voices would be about equally loud. Choir singers, especially in amateur choirs, tend to vary a great deal in the strength of their voices (Coleman, 1994). To make things more complicated, the power output of any voice increases with frequency, so that sopranos produce more decibels than basses, even when both sections are singing in ***mezzopiano***, for example. Again, as listeners, we are familiar with this difference, and compensate for it subconsciously. But it will affect the choir singer's ability to make out the own voice.

Sound propagation in a room

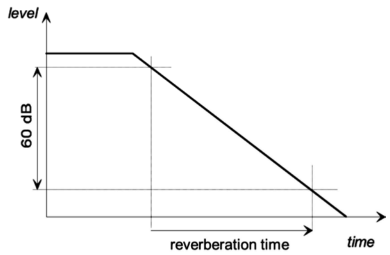
The sound of the other singers that reaches your ears arrives along three paths: the *direct* sound, the *early reflections*, and the sound that *reverberates* in the room. For our discussion of hearing Self and Other, we will consider here only the direct sound and the reverberation. The direct sound is that which travels straight from another mouth to your ears. The direct sound becomes weaker as the distance is increased: the so-called *law of distance* tells us that with every *doubling* of the distance, the intensity at the receiver drops by 6 decibels. If the choir singers are standing close together (close spacing), then this distance is small and the sum of the direct sounds from the immediate neighbours will be rather loud. This means that it will be harder to hear one's own voice, in close formations; and this will hold for *all singers* in the choir. Singer and audience preferences for choir spacings have been studied extensively by Daugherty (for example, 2003).

The reverberated sound, on the other hand, is the sound that bounces around the room. When it comes to sound, normal rooms are rather like halls of mirrors. Every singer gives rise to a large number of mirror images, and these mirror images, too, act like sound sources. This is why a single voice can sound like an ensemble in a very reverberant space. Such secondary sources are weaker, and somewhat delayed with respect to the direct sound (the sound has travelled further before reaching the listener), but they all contribute to what is called the *diffuse field.* By this we mean all the sound that is bouncing around more or less randomly until it is finally absorbed by the walls, floor and ceiling.

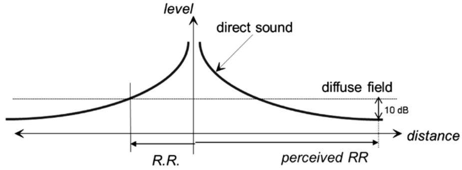
In a reverberant room, the diffuse field retains the sound energy for longer, and therefore the diffuse field is loud. In a damped room, the sound energy is more quickly lost to heat as a little of it is absorbed in the walls on each reflection; so in a damped room, the diffuse field is weaker, and the choral blend is less complete. In outdoor venues, there is no diffuse field at all.

Indoors, the sound level of the diffuse field is much the same throughout the room. This is a bit like the waves on the surface of a swimming pool, which after a little swimming will have much the same height across the whole pool. Once the swimmers have climbed out, the water surface eventually comes to rest. By the *reverberation time*, we mean the time it takes for the sound level of this diffuse field to become 60 dB weaker, once the sound source has gone quiet. The reverberation time needs to be less than one second in assembly rooms, about one second in theatres, up to two seconds in concert halls, and often more in large churches.

Another useful room acoustic metric is the *reverberation radius*. This is the distance from a sound source at which the level of the direct sound is equal to the level of the diffuse field arising from the reverberated sound of that source. So, if the reverberation radius of the room is, say, two meters, then the diffuse field will dominate over the direct sound if you are more than two meters away from the source. Curiously, our sense of hearing is so good at detecting the direct sound that we only *perceive* the diffuse field to dominate beyond a distance of about three times the reverberation radius.



The **reverberation time** is the time it takes for the level of the diffuse field to drop by 60 decibels, after the source has gone silent.



The **reverberation radius** is the distance from the sound source at which the levels of the direct and diffuse sounds are equal.

The sound level of your own voice

If you sing on your own in a room, then the Self signal is the direct airborne sound, plus the bone-conducted sound. The level of the bone-conducted sound is inside our heads and is very hard to measure; but on the other hand, there is very little we can do to change it, either. We therefore simplify things by saying that the level of Self can be taken to be equal to the level of the *airborne* signal at the singer's own ears. (The error will usually be small.) If no-one else is singing, then there will be also a diffuse field from the reverberation of your own voice; and we will consider this diffuse sound to be a part of Other, even if you made it yourself. In most rooms, this diffuse field is some ten or twenty decibels weaker than the direct sound, but for solo singing it is still important for giving the singer a sense of "room support". That's why it's nice to sing solo in the shower, where the reverberation is often relatively strong: your voice produces a lot of decibels with modest effort. As yet, no acoustical studies have been published of choir singing in a shower.

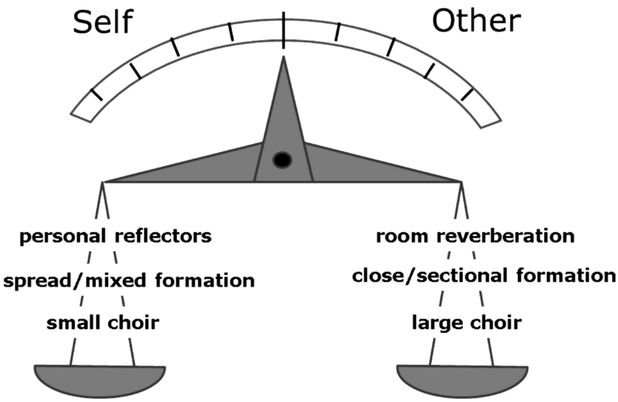
So much for solo singing; however, once the rest of the choir starts singing, you will not be able to discern the reverberation of your own voice, because the sum of all Other sounds will be much louder. Now, if you have problems hearing your own voice, because of Other being too loud, can you somehow regulate the level of your Self sound? Yes – for example, you can hold one hand as a reflector 5-10 cm away from one cheek, which makes your own voice a little easier to hear. Or, if you are holding a binder with the scores, you can angle the binder carefully so that it reflects the sound of your voice up to your ears. You will have to experiment a little to find the exact positioning that works. This can make a useful difference in some situations. You can also reduce the level of Other, and increase your bone-conducted sound level at the same time, by blocking one ear with a finger, but this is usually not a good idea. Why? Because it leaves you with only the very lowest frequencies of your own voice to guide your intonation, and there is an auditory phenomenon which can shift your sense of pitch for such dull sounds. And it looks silly, too.

The sound level of the rest of the choir

The Other sound is the sum of the direct sounds from all the other singers in the choir, *plus* the diffuse field that is the reverberating sound from the whole choir. The direct sound is dominated by the singers standing right next to you. The further away they are – the more spread out the choir formation – the weaker the direct sound will be. So a large spacing reduces the level of Other. If some singers are closer to you than the reverberation distance of the room, which is usually the case, then their direct sound will dominate over the diffuse field. But the majority of the choir's voices will reach you mostly as diffuse sound. So the room absorption, which governs the level of the diffuse field, also has a strong influence on the level of Other.

The Self-to-Other Balance

Let us now summarise by considering how all these things combine, to create a certain proportion of Self to Other. This figure shows things that increase Self on the left side, and things that increase Other on the right side.



The *Self-to-Other Ratio* (SOR) can be specified and measured in decibels (Ternström, 1994). For example, if the SOR in a particular room and choir position is +5 dB, this means that a singer will hear his/her own voice about 5 decibels louder than the sound of the rest of the choir. I measured the SOR in several choirs and found that it was around +4 dB in chamber choirs (Ternström, 1995). I also did an experiment to find out which SOR would be preferred by choir singers (Ternström, 1999), and found that the average was about +6 dB. This number can be useful to acoustics consultants; however, the range of personal preferences of the individual choristers was very large, from 0 dB to +14 dB or so. There was some indication that one's habitual position in the choir is related to one's SOR preference. So nothing is quite simple. In a later study (Ternström, Cabrera and Davis, 2005) we found that in the opera chorus on stage, the SOR's are much higher, around +12 dB. This is because the opera stage area is rather absorbent, so opera chorus singers hear mostly themselves, and not much of the others or of the orchestra.

More on choir acoustics

We have dealt here with the issue of the balance of Self-to-Other; and this is just one example of the many very fascinating aspects of the acoustics of choir singing. For example, we have said nothing here about how aspects of intonation, voice timbre, hearing or vocal control can be illuminated through a scientific approach. For more reading, try visiting the website of the International Journal of Research in Choir Singing, IJRCS, which can be found at **www.choralresearch.org**.

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