POLITECNICO DI TORINO

Master’s degree in Cinema and Media Engineering

DESIGN OF AN ACOUSTIC SHELL FOR THE POLIƎTNICO, THE CHOIR OF POLYTECHNIC OF TURIN

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ABSTRACT

The purpose of the thesis is to lay the foundations for the design of an acoustic shell for the choir of Polytechnic. Starting from an analysis of choral research carried out by other scholars concerning choral singing, the configurations and the spacing adopted by the choirs, I focused on the study of the Self-To-Other-Ratio parameter. This indicates the ratio in dB between one's own voice and that of the other singers; indicates how much a singer hears his voice compared to that of others. With four binaural microphones it was possible to perform parameter measurements for four choristers (one per section) both outdoors and indoors (clarification in the internal courtyard of the Polytechnic and in the Aula Magna). The parameter was measured in four configurations asking the singers to change their position. Consequently, with the help of a script in matlab I analyzed the data and thanks to the questionnaires I could find out which configuration reported the optimal value. In the last part of the thesis, on the other hand, the foundations have been laid to optimize this parameter with the aid of an acoustic panels.

1 THE HUMAN VOICE

Human voice is the sound produced by the vocal cords, two muscular structures vibrated by the air exhaled by the lungs. The sound is then modulated by the resonances of the cavities of the vocal channel: pharynx and mouth. (1)

1.1 PRODUCTION OF THE VOICE

The vocal phenomenon can be subdivided into three distinct events:

1. Breath production (respiratory system);
2. Sound generation (respiratory system);
3. Sound modulation (upper part of the digestive system).

Voice is influence by the body. The posture, for example, can condition it due to its incidence on the pharyngeal tract of the vocal channel which determines the resonance frequency; the larynx can be affected by the abdominal belt while the color of the voice is determined by facial expressione.

1.1.1 The vocal tract

The vocal tract consists of three essential parts (2):

- Larynx, regulates the opening of the lungs to prevent or not air emission (1);
- Pharynx;
- Oral cavity.

The pharynx and the mouth are bounded by the tongue, which can modify the volumes and the resonance frequency (1).

The overall length in men is 17 cm, while in women it is 14 cm.

Its geometry defines, through resonances, the spectral behavior of the voice: formant frequencies are created. The spectral components of the sound that fall nearby the normal oscillation modes of the contained air column are strengthened, while the others are attenuated. Knowing how to exercise control over this mechanism, the voice can be shaped according to the desired timbre and volume. Finally the openings of the mouth and nose propagate the sound waves in the surrounding space.

1.1.2 Breathing

1.1.2.1 Anatomy

The voluntary control of respiration occurs mainly by commanding four muscular systems:

1. *Diaphragm.* Laminar muscle that is located around the lower edge of the rib cage and the spine. It has the shape of an asymmetric dome because on the right it reaches the height of the nipple while on the left a lower edge remains. It is an inspiratory muscle or, flattening due to the contraction, it pushes the bowels downwards.
2. *Abdominal system.* Consists of four laminar muscles. They are located above the coasts and below the basin. During breathing they take care of containing the abdominal bowels during

inhalation and pushing them upwards during exhalation. In this case we speak of abdominal breathing.

3. *Dorsal system.* Has the task of balancing the action of the abdominal muscles; some dorsal muscles, together with the intercostal muscles, raise and lower the ribs in a costal breathing.
4. *Cervico thoracic skull system.* Rays of muscles that, being attached to the skull and the cervical spine, can pull the chest upwards for apical or clavicular breathing.

The lungs are located between the diaphragm and the rib cage. These have the task of exchanging the oxygen of the air with the blood. The bronchial trees that allow the alveoli to communicate with the outside are gathered in two main bronchi that flow into the trachea, which in turn ends with the larynx. The respiratory canal continues with the pharynx and nasal cavities.

1.1.2.2 Respiratory mechanics
Breathing is divided into two phases:

1. *Inspiration*. The contraction of the diaphragm, the relaxation of the abdominal muscles and the raising of the ribs determine the increase in the volume of the thoracic cavity. This leads to the formation of a pneumatic vacuum. Due to the pressure difference between inside and outside the air inflates the lungs restoring balance.
2. *Expiration*. The abdominal wall contracts by pressing the viscera upwards, the ribs are lowered closing the walls of the thoracic cavity, the lungs are compressed and the air contained is made to escape in the form of breath.

In this case we talk about combined breathing. Produces greater respiratory efficiency.

1.1.3 Voice generation

1.1.3.1 Anatomy
The *larynx* is the trachea closing organ. It consists of a cartilage skeleton in which the vocal cords and muscles necessary to perform the functions of occlusion and phonation are inserted. The skeleton consists of three cartilages:

1. *Cricoid cartilage.*
2. *Arytenoid cartilages.* They are attached to the posterior ends of the vocal cords and determine, through their movement, the opening (*abductor muscles*) and closure (*adductor muscles*).
3. *Thyroid cartilage.*

Between the last two cartilages are the vocal cords and between them is the glottis.

1.1.3.2 Vocal cords
The vocal cords consist of two folds of tissue and are located in a short cavity: the larynx. They are joined to one end to the thyroid cartilage (Adam's apple) and to the other to the arytenoid cartilages (mobile). They have the task of modulating the pressure of the flow passing through the glottis and from which they are put into vibration. Their oscillation frequency determines the height of the sound.

They vibrate due to the opposition of the pressure exerted by the pulmonary air and the muscular tension: the first tends to divide the vocal cords, while the second tends to unite them. Tension acts as a resilient restoring force, so greater tension produces a higher sound. The oscillatory motion of the strings is given by the periodic opening and closing of the glottis: in this way the gaseous flow is modulated. Energy comes from the drive of *Bernoulli* whose theorem states that a perfect fluid, due to the conservation of energy, cannot vary the sum of the following three terms: pressure, kinetic energy and gravitational energy. In the case of a gas, since the gravitational energy is very small, the sum of pressure and kinetic energy must remain constant: the higher the speed of the gas, the lower the pressure that it exerts on contact surfaces must be. By neglecting the speed of the gas inside the pulmonary cavity, I can obtain the thrust of *Bernoulli* (2)

$$F_B = \frac{1}{2}\rho u^2 S = (P_i - P_e)S$$

Where:

$\rho =$ *air density;*

$u =$ *speed over the glottis;*

$P_i =$ *internal pressure of the lungs;*

$P_e =$ *supraglottic external pressure;*

$S =$ *surface of the glottis exposed to the flow.*

By increasing the pressure difference, $(P_i - P_e)$, the gas increases its speed and the glottis tightens. The thrust presents a maximum, when the glottis is tightened, and a minimum, when the vocal cords are spread. The gaseous flow has a triangular shape as there are a series of overtones above the fundamental tone.

Sundberg in *"The Source Spectrum in the Singing Voice"* showed that in the transition from low to high frequencies the spectral content decays rapidly in amplitude, with an average envelope corresponding to a 12 dB drop per octave. This means that the *nth harmonic* has a width n^2 smaller than the fundamental one. By varying the tension and the spreading of the vocal cords with the laryngeal muscles, the singer can control the spectral envelope.

To produce a high-pitched sound the muscles, as well as stretching the vocal cords, lengthening them, reduce their effective length by keeping them together for a certain length. At the lower frequencies, besides the vocal cords, the surrounding tissues also vibrate; in this way the oscillator inertia increases.

When the fricative consonants are pronounced (eg */f/*, */s/*, */sc/*) the vocal cords are completely open. The occlusive consonants (such as */p/*, */b/*, */t/* and */k/)* instead are produced through a sudden release of pressure through the lightning-like opening of a septum.

1.1.3.3 Mechanics of voice generation

The *tongue*, through the contraction of its muscle fibers, contributes to tension the vocal cords.

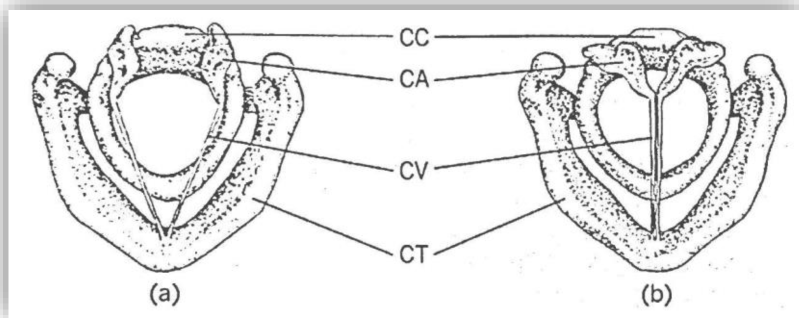


Figure 1 (a) Vocal cords in the inspiratory phase; (b) Vocal cords in the phonatory phase: CA=Arytenoid cartilages, CC=Cricoid cartilage; CT=Thyroid cartilage; CV=Vocal cords (1)

In the *inspiratory phase* the rotation of the arytenoid cartilages allows to remove the vocal processes between them and the extremities of the vocal cords determining the opening of the glottis. The respiratory muscles allow air to enter the lungs which follow the descent of the diaphragm, dilating and dragging with it bronchi, windpipe and larynx.

In the *phonatory phase* the arytenoid cartilages rotate backwards and slide sideways so as to bring into contact the vibrating edge of the vocal cords which enter into vibration due to the air pressure. The vocal cords vibrate based on the phonatory mechanisms used.

- *1° Mechanism*: the adductor muscles of the arytenoids make the vocal cords close, while the tilting muscles of the thyroid cartilage ensure the strength of attack of their front ends. The vocal cords perform the function of closing the pulmonary reservoir. If the force of contraction is lower, the vocal cords enter into vibration and produce the first fifth of the vocal extension.
- *2° Mechanism*: the arytenoids accentuating their rotation stretch the vocal cords backwards; in this way another fifth is added to its vocal range.
- *3° Mechanism*: the vocal cords are passively stretched through the action of the tilting muscles; an additional fifth is added to the vocal range.

There are three types of phonatory behaviors

1. The three mechanisms come into action one by one. In the three regions of height (registers) the voice takes on different tonal colors;
2. The active contraction of the first mechanism is reduced while the second and third enter into action simultaneously; there are no changes of timbre at the different heights, therefore we speak of the absence of registers and of passage;
3. Active contraction present in all registers, the timbric character of the scream remains throughout the extension.

1.2 VOICE'S FORMANTS

The larynx generates a sawtooth-shaped signal with a structure of harmonics of decreasing amplitude from the bass to the high. This sound then widens into several cavities among which the largest are the pharyngeal and buccal. Their volume determines the resonance frequency: the harmonics that have a vibration frequency corresponding to the resonance frequency of the cavity crossed are amplified. Since the shape and size of the two cavities are not determined, the amplification does not occur for single harmonics but for a group, called "*formants of the timbre*" (formants). The shape and size of the canal cavity varies continuously based on the articulatory movements of the jaw, tongue and lips. As they vary, the resonance frequencies of the two cavities also change and the voice can take different timbres. When these become systematic one speaks of *vowels* (1).

The vocal spectrum envelope can be expressed as follows (2)

$$vocal\ sound = source\ spectrum \times modulating\ envelope \times radiative\ efficiency$$

1.2.1 Vowels

Formants change from vocal to vocal: the particular arrangement of the vocal tract allows you to switch from one vowel to another.

The two lower formants are sufficient to characterize the vowels. What makes the vowel sounds distinguishable is the relationship within the phonetic system of the speaking subject. Depending on the position of the tongue, three types of vowels can be determined (1):

- *Front vocal*: */i/*. The tongue is pushed forward and the frequencies of the first two formants are in a 1 to 10 ratio
- *Rear vocal*: */u/*. The tongue is retracted and the lips are protruding; the back of the back touches the upper wisdom teeth and the vocal channel reaches its maximum length.
- *Medium vocal*: */a/*. The tongue is in a state of rest.

In the first two, */i/* and */u/*, are present high formants. The other vowels are determined through intermediate attitudes.

Depending on the language used there are differences, for example in the French the nasal vowels are used. The nasal and anti-resonance formants are formed when the palatal veil does not completely block access to the nasal cavities which, in this way, can be traversed by the vibrating air column.

The band of frequencies of the formants is independent of the fundamental frequency.

1.2.2 Consonants

The articulatory movements determine the occlusion or the narrowing of the vocal channel: the opening and closing phases of these movements change the volumes of the resonance cavities and consequently the formant structure (of the timbre) of the vowels preceding and following them. These variations are perceived as consonants. The occlusions and the constrictions are realized by opposition of the lips and the tongue with the upper incisors, the hard palate and the palatine veil. Articulatory maneuvers in most cases give rise to two types of consonants: *deaf* (no sound emission) or *sound* (with sound emission). If the occlusion is complete and followed by a brusque opening we speak of *momentary consonants*, if instead the vocal channel suffers only a restriction and the air emission can be prolonged we speak of *continuous consonants*.

Occlusive consonants: complete occlusion of the vocal channel obtained by approaching the lips (bilabial consonants */p/* e */b/*), support of the apex of the tongue to the incisors and the upper gums (dental consonants */t/* e */d/*), support of the back of the tongue in backward places of the hard palate and of the soft palate based on the vowel to follow (palatal consonants */k/* e */g/*). The explosive consonants are determined by an interruption of the voice at the time of occlusion while the explosion occurs in the act of release. The spectrum is very extended in frequency but the ear perceives the area of maximum intensity. In German and in the Tuscan pronunciation we also have the aspirated consonants, or occlusive consonants in which between the explosion and the following vowel we hear a breath.

Nasal consonants: Produced by the articulation of a sound occlusive consonant in which there is a lowering of the palatal veil.

Lateral consonant: The tongue makes contact only with the middle part of the arch of the upper incisors and the alveoli or palate; in this way the occlusion of the vocal channel is incomplete and therefore the vibrating air column escapes to the sides. For example, */l/* (incisors and alveoli) and */gl/* (palate). They have an acoustic structure similar to that of vowels.

Vibrating consonants: The vibration of the tongue and uvula causes short occlusions separated by vocalic moments perceived as vibrating consonants, /r/ apical (the French /r/ corresponds to the uvular as there is the vibration of the uvula). This consonant is determined by an interruption.

Constrictive or fricative consonants: by placing the upper incisors on the lower lip, the labiodental consonants */f/* and */v/* are produced; forming a narrow and short channel between the predorsal part of the tongue and the alveoli to make the air flow incise on the margin of the upper incisors, there will be alveolar consonants */s/* while with the lengthening of the narrow passage we have the preparetal */sc/* and */j/*.

Semiconstructive or affricate consonants: at the same point of articulation there is a combination of maneauvers of an occlusive and a fricative.

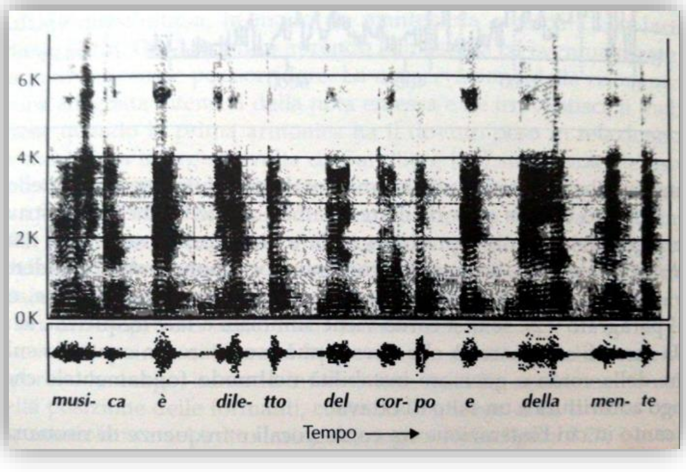


Figure 2 Sonogram of a sentence pronunced by a male voice. Since the consonants are not defined by a blackening in the sonogram they are difficult to recognize (2)

1.3 SINGING

The oscillation of the vocal cords determines the height of the sound. Tone and intensity, on the other hand, are also determined by the lungs and the vocal tract.

Vocal tracts differ between singing and speech: the larynx is lowered, the pharynx widens, the jaw is more open, the tongue and lips can assume unusual positions. The opening of the mouth produces an increase in formant frequencies, while with the enlargement of the pharynx there is the opposite effect (2). The vocal cords are subjected to a different tension. In speech the intonation of the voice varies continuously without ever settling on a given frequency. When it tends to stabilize it takes the form of singing; in this case the tonal range and intensity increases. Based on the technique used, acoustic energy is displaced between the different zones of the spectrum with changes in intensity and bandwidth of the singer's formant (1).

The extension of the musically useful voice is about two octaves and depends on the vocal technique used (1).

1.3.1 History

GREGORIAN CHANT (3)

This term defines ecclesiastical music until Humanism (a period in which polyphony is born). It is considered cult music until the Counter-Reformation. Features:

- Monophonic;
- Without instrumental accompaniment.

According to tradition it takes its name from Gregorio Magno, who tried to maintain the purity of the song by removing it from profane influences. The Church had the ability to keep music "pure" thanks to its catalytic role: in addition to protecting human lives, it kept treasures of art and culture within its walls.

Since the voices of the faithful were not considered suitable for intoning the hymn, it was initially forbidden for women to sing in church and subsequently also to men: from this moment the ritual songs had to be sung by members of the priesthood. The concept of cantor was born and in 590 Gregorio Magno established the *Schola Cantorum*. The female voice was considered unsuitable to represent Christian spirituality as it was considered without a soul.

In the early Middle Ages a profane song began to be developed in Latin banished from the Church: diffused by a rambler saltimbanco, its strength was the contents it expressed.

TROUBADOURS AND TROUVÈRES (900-1300)

This type of music is characterized by two elements:

1. Rhythm;
2. Vulgar languages (make the melody more lively and elaborate).

The concepts expressed in these songs are totally different from those of Gregorian chant: we refer to earthly values, sensitive to nature, to beauty, to women who in this context are compared to angelic beings.

The troubadours of the south of France are aristocrats, ladies, princes and lords of the castle who enjoy composing refined lyrics. These lyrics are collected in collections called chansonniers and are divided according to the topics covered. What characterizes this poetic is the idealization of women as opposed to the role assigned to them by the Church so far: the theme of the *Amor Cortese* is born.

The features found in these works are the following:

- Extension not exceeding one octave;
- Melodies accompanied in unison by some instrument (like a viella).

The troubadours spread in northern France thanks to Eleanor of Aquitaine who gathered them in her court. The lyrics are written in the *oil language* and are simpler than those of the troubadours, but the forms and poetic structures remain the same. The trouvères is accompanied by a *joueur* who plays the viella or a small harp with seven or more strings.

Polyphony

The choir has the structure of a reduced society: each of the elements contributes to building a cathedral of sounds. It has the ideal of sociality; everyone helps to form the whole. The first forms of polyphony were born in situations where men and women sang together, in gathering places where people were after work. Thus the song with two or more voices develops.

The *counterpoint* spreads: two parallel melodies, in which each note of the first corresponds to one of the second. From the middle of the twelfth century onwards, polyphony also took effect in churches. The *Ars Antiqua* begins. The most developed form is the motet: a three-part composition, the inferior (tenor) performed with one instrument while the other two (duplum and triplum) are each sung with a different text (in Latin or in vulgar language depending on the destination, liturgical or profane). In *Ars Nova* the polyphony of the voices becomes richer and more alive. With *Guillaume de Machaut* we start talking about *isorhythmia*, that is, the identical representation of the rhythmic structure of a melodic phrase in successive moments and with different notes. In addition to France there is talk of Ars Nova also in other countries but in this case the polyphony remains simple. In Italy, for example, music is seen as an expression of the joy of living rather than as a mathematical and intellectual exercise.

The polyphony reaches its maximum expression in 400 thanks to the Flemish masters. The motet, from 1450 only becomes vocal and divided into four voices: *superius*, *altus*, *tenor*, *bassus*. Since female singers were not admitted into the Church the roles *superius* and *altus* were played by falsettist men and *pueri cantores*. In secular music instead they were entrusted to women. Later a fifth part was added, usually a tenor who reinforced the acute part, a sixth, seventh and eighth in which there was talk of a double choir. *Okeghem* came to compose a *Deo Gratias* for 36 voices.

During the fifteenth century, Italy specialized in profane music and developed a sense of individuality: a tendency to give more importance to the upper voice by grouping the others into a homophonic counterpoint easily executable by an instrument like a lute.

Vocalism of the Renaissance

The catalyst of *Renaissance* music is the perfect balance between the parts; this, however, is not reflected in the society dominated by continuous epidemics.

The motet falls into disuse and the favorite form becomes mass. This develops along two different paths: one vowel ("canto a cappella") and another based on the instruments that will give the music a new dynamic aspect.

The main form of the sixteenth century becomes the *madrigal*. Initially it takes up the concept of *homorhythmia* and the text is of a lyrical, spiritual or loving topic. Towards the end of the 500 it is written for five, six voices: each voice acquires individuality and differs from the others.

In the sixteenth century vocality is linked to the concept of family: the voices share the same phonation system and their timbres differ more for the diversity of register height than for the color.

With Lutero, in Germany, the *choral* was written in 4 voices and the simplest one was sung by the faithful. The texts were written in German although they were of profane or Gregorian origin.

The seventeenth century

In this period there is a revaluation of the voice that in the sixteenth century had assumed a more "instrumental" dimension. During the end of the century the musicians would meet at the home of Earl Bardi, in Florence, and theorized a perfect symbiosis between music and word. According to Vincenzo Galilei music had to express the feeling of words and the words themselves had to be always understandable and spelled out. Later they started talking about *reciting singing*. The singing virtuosity should be banned for greater comprehensibility of the text.

Throughout Europe the center of social encounters moves from the Church to a more secular place, the theater. The audience was reserved for people of modest conditions who remained standing throughout the show, instead the most expensive places were those on the sides of the stage. The theater was so successful that people of different ranks began to frequent it. The *Opera* is enriched thanks to technical innovations and changes the theme: from pastoral fables it becomes mythological and historical. It moves more and more towards the *monody* and the melody is often accompanied by a continuum bass. Especially in Rome the scenes are enriched with various elements, characters and comic situations, with the aim of re-establishing an emotional balance in the spectator. The structure of the *aria* is codified: it is detached from the recitative and the psychological situations can be classified (for example, one can find arias of "doubt", "storm" and "sleep"). The song is differentiated also according to the scenic needs and the music. The distribution of the parts is formalized with *Monteverdi* and *Cavalli*. Alessandro Scarlatti is responsible for the codification of the work: three acts; initially there is a symphony and it continues with recitatives and arias; at the end of each act there are concerted with all the characters of the melodrama.

The Italian opera of the seventeenth century also spread to France, to Paris, although the doodles and passionate vocalizations were not so much appreciated by the more rational French. *Gianbattista Lulli* elaborated a form of the opera more suited to the French spirit, devoid of concessions to bel canto and extremely coherent from a dramatic point of view.

During the *Baroque*, the three main vocality paths differ: theater, church and chamber. For the theater the style was vague and mixed; for the chamber it was mimed and flowered, while for the Church it was affectionate and grave.

The *polyphonic choir* became more and more incomprehensible, so new vocal forms arose. The *oratory* was very successful: a form of entertainment that united soloists, chorus and instrumental accompaniment, but that differed from the opera in that there were no scenes. The themes were taken from the Bible, the text could be both in Latin and in the vernacular: one character had the role of "historian", the soloists were involved in the dramatic part while the chorus concluded with moral comments. In the eighteenth century the *oratory* became similar to the form of melodrama.

In the seventeenth century the *cantata* also developed: any song that should be sung and that normally included a recitative and an aria. The structure was divided into one or two dialoguing voices with harpsichord accompaniment. Thanks to Bach he was very successful in the Protestant Church, with the involvement of choir, orchestra and obligatory instruments.

The eighteenth century

The arias became so important that a type of opera developed that brought together the most popular of the time: this type of show was called *"mess"*. At this time *castrated* were successful, considered the initiators of the golden age of bel canto. Their success was due to extraordinary vocal abilities (it is whispered that their voice could cover three octaves, therefore all four registers of the human voice), with lung capacities higher than the average that allowed him agility and power superior to those of the female voice. All these singers were united by a great career that brought them riches. As the Church considered the demonic female voice, it welcomed these boys very happily. For this reason, many poor families decided to make their children take that path, but of course not all of them became successful. The golden age of these singers ended with *Romanticism* in which the characterization of the characters was based on the contrast between male and female character. Until then the roles were characterized by timbre instead of sex.

In this period in London there is a good exchange between singer and composer. *Haendel* manages to put the accent on the singer, relegating the scenic fictions to the background.

The melodrama began to fall apart: intermezzi and musical comedies began to be inserted between one act and another. Initially it became real comic operas; later it became sentimental. The arias were ritualized. People met in opera houses to discuss business, bet on singers or on the gaming tables; in this perspective the tragedy no longer made much sense. In this context, more attention was paid to the funny interlude which was more in line with the new emerging class. In this period the vocality is increasingly extended upwards.

The nineteenth century

The theater remains the place of excellence to do business, start loving affairs.

According to Rodolfo Celletti Rossini the nineteenth century represents a new golden age for vocalism: it overturns the concept of melodrama (in which music must be subordinated to the word) and lets emerge the baroque concept of dominant fantasy. Coloring and ornamentation are not seen as virtuosity but as integral parts of the opera. It remains tied to the vocal ideal of the castrated and singers capable of great expressiveness. This Rossinian period is very demanding regarding the vocal technique: the voice must be flexible to the wishes of the singer. Rossini tried to modify the structure of his works, especially at the orchestral level, with the new proposals of Romanticism: the bel canto based on abstract poetics proposes the search for truthfulness and dramatic truth. In this perspective, Rossini managed to create only one opera: *Guglielmo Tell*. Then he left room for new recruits.

Romanticism comes from German youth linked to the ideals of the French Revolution. With the restoration the ideals are transformed and we begin to think of the opera as a usable asset. The bases of this are set by Gluck who tries to restore dignity to the dramatic action of the opera seria. The public, unlike the eighteenth century that saw the moment of the opera as a moment of sociality, actively participates in the fate of the character. For this reason there is a need to understand the dramatic logic and the words that were sung on stage. Romanticism is diversified according to the environment of development: for the Germans there is the recovery of the ideal of nature seen as an element in which to sink the melancholy and take refuge from a difficult world; for Italians instead it means feeling and passion. Heroines and heroes were dressed in everyday clothes and the ideal of royalty was represented by figures who composed the court and not through the king himself. Often, the tragic ending accentuated the sentimental aspect of the work.

The song introduced a new element: the hysteria and the neuroticism of the phrasing; lost its connotation of unreality. The voices were reclassified according to the new order that the various colors and stamps claimed: for example, the female contralto fell into disuse, the tenor appropriates the role of lover, the baritone played the role of elder brother or antagonist, the bass had noble roles of father king or priest; the female soprano in this period acquires the meaning of purity, candor, hysteria and madness.

Opera became a flag of the unity of Italy against the Austrian forces. With Giuseppe Verdi there is a reinvigoration of the voice. From this point of view we move on to verism which pursued the myth of realism in an almost maniacal way. A series of short works were born which dealt with love dramas consumed within a peasant or sub-proletarian world. In musical terms it was difficult to achieve realism. The song had to express the concepts of realism and the melodic line was the most immediate expression; the characters were prey to their own impulses. For these reasons, the verist composers continuously sought the so-called "melodic vein". The *verismo* accentuates the expressive side of the vocality to the detriment of its musicality. In this period the "*bel canto*" is definitely finished: the song is conceived in a different way.

In Germany Romanticism develops with very deep emotional and human characteristics: love for nature, the fantastic and the recovery of strictly German themes. The German vocality follows more the evolution of instrumental music. *Richard Wagner* is considered the pinnacle and conclusion of Romanticism: union of acts, joining of sounds, importance given to the breath of the orchestra, loss of closed forms, introduction of *Leitmotiv* (musical theme combined with each character, feeling or idea of the opera that served to highlight its appearance on stage). The human voice becomes symphonic; there is no longer the opposition between melody and harmony. Types of voice are created with a volume that allows them to compete with the orchestra, for example the strength tenor. According to Robert Donington the only way to find his vocal space in a Wagnerian orchestra is to have a loose technique based on the principles of *bel canto*.

In France in this period no particular vocality develops but towards the end of the century French music will be characterized by impressionism.

In this period also a more intimate and delicate way of singing develops that flows into the *Lied*: forms of composition in German language accompanied by music characterized by the quality of the text. There were no ornamental blooms to keep the wording clear.

In the mid-nineteenth century a new form of composition was developed, the *Chanson*; this takes hold above all in *café-concerts*: a public venue that presented its customers with a varied musical performance.

TWENTIETH CENTURY

The musical phenomenon expands with the development of the record industry and the widespread growth of the media. Emphasis is placed on the commercial aspect of music: the content is not given importance but the quantity of media sold. In this period there is the recognition of a new vocalism very different from the previous one in which the emphasis is on expressiveness. In Europe there is a tendency for singing to become a new form of non-singing: the voice takes on the task of reflecting the dark and hidden side of human personality.

1.3.2 Singer’s formant

The singer's formant is a formant that is accentuated at around 2500Hz. It is determined by an alteration of the first resonant cavity of the vocal tract caused by the following factors (2):

- enlargement of the pharynx;
- lowering of the larynx.

The last increases the volume of the sound leading to a distortion of the vowels compared to speech.

The singer's formant produces two important effects:

1. It gives the male voice greater polish;
2. Invigorates the voice.

The singer's formant is independent of the vocal sung and his height. Despite being an essential feature of the male voice it can also be found in contraltos. In fact the female voices already have a third natural formant quite acute and intense not to require the development of a special formant. When they have to issue high notes, singers tend to strengthen the higher formants. In choral performances the formant of the singer is used only in an attenuated way as the goal is to blend the voices.

1.3.3 Adaptation of formants

When the fundamental frequency of vibration of the vocal cords rises above the first formant, the female voices are able to raise it so as to keep it tuned to the carrier frequency. This is achieved by opening the jaw and pushing it forward as if to smile. Preserving the resonance guarantees an adequate intensity of the note emitted and strengthens its timbre.

In man the vocal cords are less free to oscillate. For this reason, if one tries to raise the first formant to the frequency of the sung note, a change in the oscillation frequency is produced.

In the singing of *lama* (Tibetan monks) the vocal cords are trained to produce a very low frequency vibration (about 70Hz). The tension acting on the vocal cords must be very low and the strings relaxed. In this way they are very sensitive to pressure waves associated with stationary modes established in the vocal tract. This ensures that there is an octave between the first and second formant.

1.3.4 Difference between singing and speaking

Ternstrom and *Sundberg* in "*Formant frequencies in choir singers*" (4) conducted an experiment with eight choristers of the bass section (their low fundamental frequencies give rise to spectra with close harmonics) to compare the forming frequencies of the speech with those of singing (considering also the soloists).

As for the professional opera singers, *Sundberg*, he noticed that they used different formants in singing than the speech (as shown in the table).

Sing	**Spoken**
The first forming frequency is higher	The second and third formants are higher (anterior vowels)
More or less stationary formants for the duration of the tone	Formants tend to change quickly
Scatter reduction in the three minor formants (when singing we tend to change the vowels)	

Table 1 Difference between singing and speaking

Professional singers group their major formants to create the singer's formant. This spectral distribution makes the voice more penetrating and makes it easier for the solo singer to be heard by the accompaniment. *Cleveland* studied the forming frequencies of male soloists (bass, baritones and tenors) and noticed a systematic increase in all formants when they ranged from bass to tenors.

1.3.5 Vocal classes

The subdivision into registers was born with the advent of polyphony (XIII-XIV century): *bass*, *tenor*, *alto*, *descant* (voice in countermelody). Initially the minor note of the bass section was do^3, or 130Hz. Over time it is possible to increase the acute register with the introduction of *the acute descant* (part, generally, entrusted to children) and of the *falsetto*: it is possible to reach the do^2. Only from the end of the 700's the frequency range of the various registers is completely developed (3).

Male and female voices constitute two separate groups: the frequency variability of female voices takes place in the upper octave of the male one. The voice has an age-related development: with puberty in males the size of the larynx increases more than in females while the position of the organ in the neck becomes lower; the voice is lowered by one octave.

The vocal classes can be summarized as follows (1):

- Bass: *Re1-Fa#3*;
- Baritone: *Labem1-La3*;
- Tenor: *Do2-Do#4*;
- Contralto: *Fa2-Sol4*;
- Mezzosoprano: *Labem2-Sibem4*;
- Soprano: *Si2-Do5*.

Figure 3 Extension of the registers (2)

The first three refer to male voices; the others to female voices.

The stylistic events of the nineteenth-century melodrama led to the combination of the vocal classes with the roles: in the lyric opera soprano and tenor are the protagonists, mezzo-soprano and baritone the antagonists while alto and bass represent the characters of greater social dignity. The classification criteria are linked to two parameters that depend on the technique adopted: *timbre* and *extension*.

Goddard in *"La voce, tecnica storia e consapevolezza del canto*" (3) lists the vocal classes in detail based on the roles of the characters and their tonal characteristics.

Voices	Features
Contrabbass	Deepest male voice. It can reach the *A* placed two octaves below the central *C*. Rare voice, is found mainly in the Russian church.
Deep Bass	Characterized by heaviness and lack of agility; has a very limited presence within the operatic tradition; suitable for extraterrestrial roles.
Drama Bass	Bass to which a certain drama is required.
Singer Bass	Lighter and more malleable timbre.
Funny Bass	Articulation difficulties are accentuated

Table 2 Features of Bass Section

Voices	Features
Bassobaritono	Hybrid voice, voluminous and dark. Extension similar to that of the bass singer but the treble of the true bass is darker.
Baritone	Category that developed in the nineteenth century; is positioned between the bass and the tenor. It interprets intense roles with human characteristics.

Table 3 Feature of Baritone Section

Voices	Features
Tenor	Emerges with leading roles during romance. The strength tenor is among the most serious tenor voices: heavier vocal quality, suitable for the German or Wagnerian repertoire (usually this type of tenor is not contemplated in Italy).
Dramatic Tenor	Voice characterized by baritone colors.
Lyric Tenor	Together with the previous one they are characterized by a strong vocal power to fill the theater.
Soft Tenor	Voice characterized by agility and color. He has the ability to transform himself into a countertenor managing to change his treble into a falsetto mixture. The low notes lack thickness.
Controtenore	Linked to a single melodic line in polyphonic compositions at the turn of the sixteenth and seventeenth centuries. An extension similar to that of the female *contralto*, it manages to feminize its voice.

Table 4 Feature of Tenor Section

Voice	Features
Contralto	Female *controtenore* equivalent; corresponds to the lowest voice of the female ones.

Table 5 Feature of Contralto Section

Voices	Features
Mezzo-soprano	Holds the role of the "bad guy" or independent woman. Usually characters with strong characters are characterized by a darker voice.
Dramatic Mezzo-soprano	Voice characterized by a darker color.
Lyric Mezzosoprano	He faces roles characterized by greater singing.
Agility Mezzo-soprano	Work on the color of the voice. It has a soft and velvety tone.

Table 6 Features of Mezzo-soprano Section

Voices	Features
Soprano	Higher female voice.
Soft Soprano	It has an extraordinary agility and flexibility in sound emission. It has the characteristic of the *staked*: vocal action that consists in the fast emission in succession of detached notes (usually belonging to the high register).
Dramatic Soprano	Voice characterized by physical and vocal resistance. It has an extension similar to that of the mezzo-soprano. The low notes take up the color of those of a contralto.
Lyric Soprano	His vocal style is characterized by a very pure timbre, a great expressive capacity and by the amazing ease in performing perfect yarns on high notes.
Pushed Lyric Soprano	Italian voice for excellence. It is similar to a dramatic soprano.
Soft Lyric Soprano	It combines the typical expressiveness of the true lyric with that characteristic of light sopranos. It takes on the color and lightness of the timbre of a light soprano (without its treble) and presents a greater body in the central notes. It has a sugary color that fascinated the bourgeois American public of the forties and fifties.

Table 7 Features of Soprano Section

1.3.6 Voice register

The registers correspond to the tonal and dynamic characters assumed by the voice based on the phonatory behavior in the different tonal regions. The worst case corresponds to the 1st type of phonatory behavior: the vocal timbre is divided into three regions by the three laryngeal mechanisms; to the three regions the register value is recognized.

Historically they have had various names: "of chest", "of throat", "of head" or "lower", "medium", "upper" or "first", "second", "third". Sometimes the first two were associated together so only two registers were recognized: "of chest" and "of head". There is no agreement even on the passage (some only recognize the passage to the acute register so they count a single passage instead of two) (1).

- *1st REGISTER* corresponds to the first laryngeal mechanism: the lowering muscles of the hyoid bone and inclinators of the thyroid gland fix the thyroid forward to constrain it to the sternum; in this way there is the active contraction of the vocal cords. The lowering muscles of the ribs accentuate the costal component of expiration. Since the vocal cords are contracted the sound produced has the expression of effort. The extrinsic muscles of the larynx transmit vibrations to the chest: chest voice.
- *2nd REGISTER* corresponds to the second laryngeal mechanism: the arytenoid cartilages passively relax the vocal cords. Towards the upper limit the cry mechanism reappears, used as a means to reach the acute. If the transition is gradual it may be unnoticed. Let's talk about mixed voice or throat.
- *3rd REGISTER* corresponds to the third mechanism: head voice, falsetto.

1.3.7 Vocal techniques

The vocal techniques identify the geographical, social and stylistic environment in which the singing takes place. There are three fundamental characteristics (1):

1. Expression (aptitude to communicate emotions);
2. Agility (aptitude for making many short notes in a short time);
3. Power (aptitude to generate sounds of great intensity throughout the extension).

They are intended as ways to use the voice to get certain musical results.

NATURAL VOICE TECHNIQUE Voices that by composition have an optimal phonatory behavior. Optimal technique for tonal extension and for the expression of emotions. It is the one with the minimum energy balance but it is not the most agile nor the most powerful.

POPULAR VOCAL TECHNIQUES They correspond to the techniques of real folk singing, such as the singing of the mountaineers or of the mondine, in Italy, or the gospel or spirituals, in America; refer to techniques related to pop music. Physical work gives harmonious muscular development; the constant commitment of the larynx accustoms the organ to an active contraction also in phonation. We tend to use the first and second register; it is difficult to reach the third due to the closure of the larynx. The vocal techniques of light music are constantly evolving: there is a tendency to preserve in the singing the tonal and expressive characteristics of the spoken voice with the use of phonatory behaviors that vary between the first and the third type. The timbre effect of the treble is achieved with the vocal behavior of the cry even if the effective extension of the voice tends to remain within the limits of the second register.

DOTTE VOCAL TECHNIQUES (Tenor Domenico Donzelli 1830) With the enlargement of the theaters and the expansion of the orchestral staff there was an imbalance between the acoustic power of the great orchestra and that of the voices. The technique used to increase the vocal power was to channel the tongue: in this way the sound is stronger than the spontaneous one. Another way is to increase the energy of muscular maneuvers.

FALSETTO Voice issued with artificial technique in the texture corresponding to the head register; in the case of men, a stamp similar to the female or infantile voice is obtained. It is obtained by closing the back of the vocal cords with a stable contraction, letting the front one vibrate and controlling the intonation with the second and third mechanism.

1.3.8 Directivity of the singing voice

The directivity of the single harmonics is greater the higher their frequency; for this reason the directivity of the voice changes according to the vowel issued. The final directivity is an average of the directives of the vowels of the text. The spectral composition of vowels is determined by the following factors (1):

1. Anthropometric characteristics of the singer;
2. Technique adopted.

The directivity has effects on the reverberation: taking for example a traditional horseshoe theater, the voices of the low vocal classes reach the listener with a more enveloping sound while those of the acute vocal classes arrive in a more directive way. The voices emitted with techniques aimed at making the tone ringing are more direct.

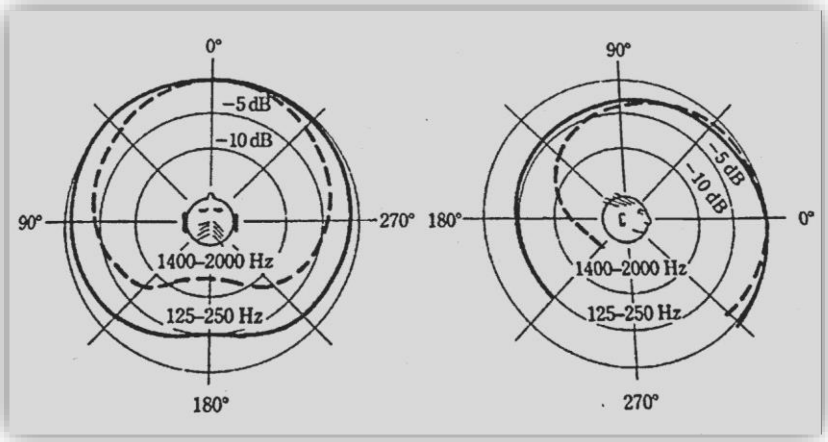


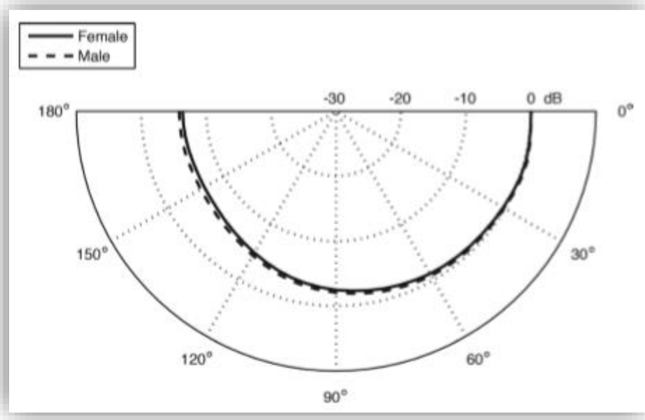
Figure 4 Directivity of the voice as a function of frequency (1)

(5) *Jers* in *"Choral Conducting and Choir Acoustics - Phenomena and Connections"* made the following considerations regarding sound propagation and direction:

- *Low frequencies (80-500Hz)* spherical propagation and negligible direction;
- *Middle frequencies (500-2000Hz)* direct propagation towards the front and the bottom; slightly lower frequencies cause greater upward propagation to the left and to the right with a reduction towards the rear. In the back there is a local maximum due to constructive interference;
- *High frequencies (2000-5000Hz)* strong spread towards the front and sides; decrease in propagation in the back.

1.3.8.1 Experiments and differences found

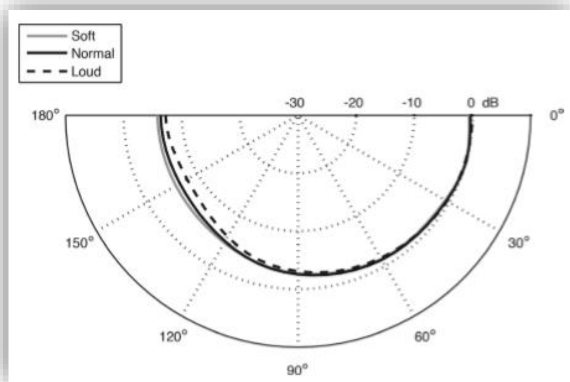
(6) *Monson* and *Hunter* conducted an experiment with 15 subjects who were asked to sing in their own style (classical / opera, classical / choral, jazz / pop, musical theater). The performance of each was performed three times based on production levels: normal, pianissimo, fortissimo. The effects found by the authors can be summarized as follows.



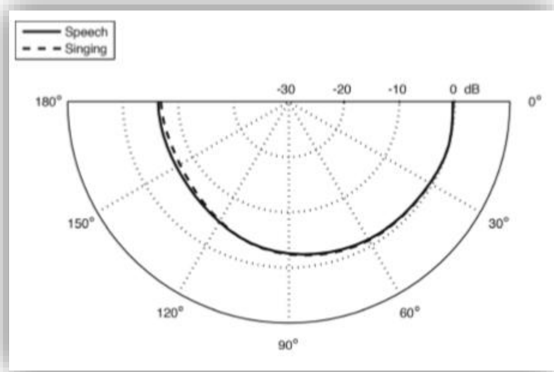
Gender Effects There were few differences between male and female singers; at 8kHz the male voice seems to be slightly more directional than the female one. This phenomenon can be determined by the size of the mouth (larger in males). Despite this, however, the differences found are minimal, they are lower than 3dB. Considering the average directivity indices (*DI*), significant differences were noted between males (1.9dB) and females (2.3dB).

Effects of the level of production As the level of production increases there has been a tendency to be more directional. The average overall values of the *DI* parameter are as follows:

- Soft Voice: 1.9dB;
- Normal Voice: 2.1dB;
- Loud Voice: 2.7dB.

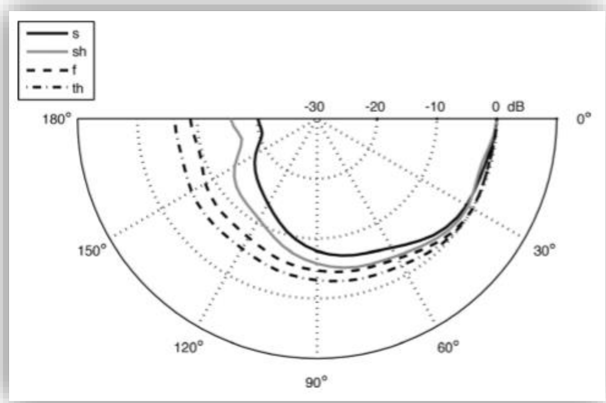


Through pairwise comparisons significant differences were noted for each increase in production level. This effect is more pronounced in the octave at 16kHz at 180 °.



Production mode effects Between speech and singing, no substantial differences were found (about 1dB). This implies that the difference in the opening of the mouth between singing and speech is not significant to make changes in directivity. The shape of the mouth depends on the style of singing used.

Effects of phonemes Differences in fricatives are noted. The */s/* is more directional than */ϑ/*. Also in the first one notices a greater energy in the 8kHz band. Humans can therefore have some type of voluntary control over directivity patterns.



(7) Other authors, such as *Katz* and *d'Alessandro*, have conducted studies concerning the vocal directivity of singers. In this case, the subject considered by the authors was a countertenor. The recording took place with 24 microphones mounted on a mobile semicircular arch in an anechoic room; moreover, through the video recordings it was possible to study the shape and the opening of the mouth. In general the following considerations have been found: greater variations in directivity models at high frequencies underlining those above 5600Hz due to the opening of the mouth.

The three aspects of the radiation models investigated are the following:

1. Differences between loud voice and soft voice;
2. Sung vocal effect;
3. Voice projection (implies a sort of spatial effect or vocal directionality control).

The experiment was conducted in the anechoic room of the IRCAM. The singer was positioned in the center on a chair with a headrest to ensure a stable position; for measurements a 180° arc was used with 24 equidistant microphones on a motorized arm with an elevation between -45° and 90°. Two types of feedback were provided to help the singer maintain a constant vocal effort; artificial reverberation was added to the headphone audio return.

The results of the experiment can be summarized as follows:

- Changes in the geometry of the mouth may involve variations in the spectral content of the vocals sung. It is noted that the low-frequency region (up to 600-1000Hz) is omnidirectional (range in which the dimensions of the head are comparable to half the wavelength); in the middle region (1250Hz - 4000Hz) there is a range of patterns in which the higher frequency bands gradually become cardioid. The amount of energy contained in the respective band must be taken into account since the perceived directivity of a sung note is a combination of the directivity pattern as a function of the frequency and energy of each band that contributes to each pattern.
- The geometry of the mouth varies with the increase in intensity; this also involves changes in the spectral content of the note. In particular we see that the harmonic near 1000Hz has a lower frequency for the mezzoforte than the other intensities; this may explain why the pattern of mid-range directivity resembles the 1250Hz band more than the others. We also

note that the geometry of the mouth for the *fortissimo* is different from the lower one and could explain the different pattern at 800 - 1000Hz.

- The term *Projection* indicates a vocal gesture, a vocal quality, aimed at filling the space of a great concert. The singer focuses his attention on the last rows of a concert hall with the idea of projecting the sound of his voice to obtain maximum power. The effect observed by the authors is an increase in energy at high frequencies: for the vowel */a/* projected in the region 5000 - 6300 Hz and the vowel */o/* projected in the region 6300 - 10000 Hz. In the spectrum of the projected voice we note two additional peaks between the first and second harmonic and between the second and third harmonic.
- In big rooms one of the problems is to be able to provide a sound level far from the scene. In conditions where the room is small and the restricted public the singer pays more attention to the quality of the voice and to the expressive nuances rather than to power and projection. The voice, in this way, is *focused* with the idea of offering a better timbre and better nuances to a chosen and close audience. For example, for the vowel */a/* focussed, there is more energy than the normal one.

1.3.8.2 Opera singers

The vocal directivity can be influenced by the opening area of the mouth (a factor that can be controlled by the singer), by the shape and size of the head and torso.

(8) *Cabrera*, *Davis* and *Connolly* measured the directivity of professional opera singers (eight professionals, six women and two men). Measurements were performed in an anechoic room with free field microphone measurements at azimuth angles at 0 °, 15 °, 30 °, 45 °, 60 °, 90 °, 120 °, 150 ° and 180 ° in the horizontal plane alternating between left and right. The microphones were placed at 1.7m and 2.6m from the mouth (the measurements were set at a virtual distance of 1m). The singers had to sing the last sixteen bars of *"Torna a Surriento"* by *Ernesto di Curtis*. The same tonality was used for everyone, considering a minor octave for males. The performance was performed in four ways with ear flaps:

1. Paying attention to intonation;
2. Emphasizing the emotional connection desired by the composer;
3. Sing as if the performance were in a large theater;
4. Sing as if the performance were in a small theater.

Finally, a last performance was performed as the fourth mode but without the use of ear flaps.

From the values of δ (ratio between the total radiated power and that of the omnidirectional part) we note that the directivity tends to increase with frequency. Generally, although singers sang the same song in the same tonality, there are substantial differences between their power spectra, both in terms of peak pattern and absolute sound pressure levels reached.

In *Vocal Directivity Measurements of Eight Opera Singers* (9) Cabrera and Davis show that the performance style did not significantly influence the directivity of the singers. Referring to the four condition set aout above, the deviation of the average SPL of each subject was influenced in the third condition (the simulated exhibition in a large auditorium), in this case in fact reaches the highest levels of SPL and intonation. It is also noted that in the simulated small auditorium condition we find the lower SPL levels. The variation in vocal directivity between the singers may be due to the opening area of the mouth (a factor that can be controlled by the singer), the shape and size of the head and torso. In the studies conducted by *Marshall* and *Meyer*, concerning the horizontal and vertical directivity of three singers, it was noted that their directivity is greater than the language.

1.3.9 Lift of the voice

The term lift refers to the attitude of the voice to propagate in space. The intensity of the vocal sound progressively decreases in space due to absorption, but the high harmonics are attenuated before the bass. The distribution of acoustic energy in the voice spectrum affects its audibility at different distances: with the same energy, voices with more intense severe harmonics reach farther. This interferes with the psychoacoustic phenomenon: with the same total energy and listening conditions, voices with concentrated energy in the high harmonics are perceived as stronger. The frequency band of the singer's formant coincides with the area of maximum hearing sensitivity. (1)

2. CHOIR

2.1 INTRODUCTION

The term choir derives from the Greek *choròs* and means song performed by several people. The choir can be of two types (10)

1. *Monodic*: all the voices of the choir sing the same melody simultaneously;
2. *Polyphonic*: the voices sing different melodic lines that intertwine or chase each other; in this case the different voices of the same gender, having the same extension and the same melody, form the parts. It is determined by a contrapuntal musical structure (musical composition technique, bord in the Middle Ages, which takes care of the combination of several melodics parts).

The choir can have equal voices, if the choristers are all of the same sex, or mixed chorus, if there are both female and male voices. The chorus of white voices is the choir made up of only children.

	Female Voices	**Male Voices**
Treble	Sopranos	High (contralti or acute tenors called falsetti); Tenors
Intermediate	Mezzo-Sopranos	Baritones
Bass	Contralti	Bass

Table 8 Scheme of the voices in a choir

The names of the voices are linked to the functions in the execution. *Soprano* indicates the voice that sings over the others; *tenor* corresponds to the item around which the other discantano (the *discant* indicates an opposite voice to the tenor and proceeds by contrary motion). The term *contralto* derives from the Greek *contra* which indicates a part destined to make harmony with another, to merge together; for this reason the contralto indicates the voice that contrasts by merging with the treble.

The most used choral writing today is the odd four-part writing: soprano, contralto, tenor, bass. In choirs with female equal voices, sopranos, half-sopranos and contraltos are used; while in the male equal choirs, often in four parts, tenor I, tenor II, baritone and bass are used.

The choir can be performed with or without musical accompaniment: in the first case we speak of the *concertante choir* (developed from melodrama and symphony), while in the second case we speak of the a *cappella choir* (culmination in the Renaissance).

The history of Western music has inherited the modern concept of chorus from Christianity, from the *chorus laudantium of the Vulgate*.

2.2 HISTORY

Antiquities

The religious ceremonies of the Egyptians, Sumerians, Hittites, Elamites, Assyrians and Jews had a mostly choral development unlike the Persians, who limited the choral manifestations to the secular feast and to the banquet where the solo singing alternated with the choir. The Egyptians, Sumerians, Hittites, Elamites, Chaldeans, Babylonians and Assyrians attributed a predominantly ritual-religious function to music.

In Exodus we find the oldest and safest documentation of a true choral event. The members of the choir were members of the Levite tribe. Davide subsequently worked on a careful choral organization: 4000 musicians and 24 classes of sacred singers. To enter the choir of the Levites it was necessary to have been in charge for 25 years and to have a pure and pleasant voice (women were excluded from choral services because their voice was considered a seduction). At the top of the musical organization there was chorality: alternation of solo and choral voices plus two semi-choir that served as the basis of responsorial and antiphonal singing.

Greek poetry we can find the choral spirit. In the Homeric poems there are choral scenes in which the distinction between the singing and dancing groups is clear. This distinction ends in the classical period of the Hellenic civilization with the affirmation of the choral lyric (in particular of the ditirambo: choir of fifty singers who, gathered around the altar, evoked the god Dionysus exalting his deeds) and of theatrical forms of tragedy and comedy. The choral lyric has the largest development center in Sparta, where it was introduced at the beginning of 600 a.C. from Talete of Crete with the form of the *Embatère* (militaristic song). Being an expression of collective feelings, it found impetus in the grandiose civil celebrations and in the connected artistic manifestations. The most used forms were the following:

- *Peana* (war song), in honor of Apollo and Artemis;
- *Pròsodo* (processional song);
- *Epinicio*, in honor of the winners of the gymnastic;
- *Iporchèma* (song for dance);
- *Trènos* (dirge);
- *Parténie* for voices of virgins;
- *Praise* laudatory;
- *Hymn* celebrating the divinity.

All these forms were based on the homophone chorus (unison singing performed by several voices); they had a first arrangement with Alcmane who invented the verses and the anti-verses. The choral composition was divided into two parts and the execution was also entrusted to the orchestra, as well as to the collective song. Subsequently Tisia introduced a third moment: the *Epòdo* in which the choir gathered in the center, near the altar of the divinity.

The best choral production period is between the 7th and 6th century a.C. with the advent of the cult of Diònisio the choral chant changes its appearance: the *ditirambo* is introduced, an orgiastic chant supported by a choir of fifty singers led by a *corifèo* (chief of the choir) around the altar of the god to evoke it and exalt its deeds. Arione di Metìmma gave form to this song by dividing it into two parts and took care of the orchestral movements to emphasize the sacrifice of the goat on the god during the ceremonies. Thespis replaced the choir leader with the priest, in charge of representing the god, and gave him the narrative part. Finally, all this led to the advent of *Tragedy*: at the beginning the choir was very important, but with the subsequent tragic authors the dimensions of choralism were attenuated by giving precedence to individualism. In the tragedy the choir took part in the following subdivisions:

- *Pàrodos* the choir entered processionally after the *corifèo* and the aulòs player (species of oboe) and arranged themselves around the altar to start the action;
- *Kommòi* (lyrical dialogue between actor and choir);
- *Stàsimi* (choral songs between the various episodes);
- *ésodo* the choir was released in the same initial order to conclude the action.

The choir, composed of twelve members, was located in the orchestra, between the proscenium and the stands (in the center there was the altar). In this case, his role was to comment on what was happening on the scne, giving back to the spectators.

As for the comedy, instead, there was a choir of twenty-four elements and a part was sung facing the public (*Paràbesi*).

In the period of the decline of Greek civilization the choir gave way to the solo element, to the consequent virtuosity and to academicism.

The civilization of Rome traced the routes beaten by the Greeks with the only difference in the number of clearly greater choristers.

Although the Hellenized emperors were music lovers, they failed to oppose the prevalence of professionalism and the rise of virtuosity.

Christianity and the Middle Ages

According to the French musician and musicologist Gastoué, the musical Middle Ages begin with the first experiences of polyphony.

With the exclusion of musical instruments during the birth of Christianity, musical manifestations developed in a choral way. The language used in the songs was Greek. The oldest choral chant practiced by the early Christians was the *responsory*, a solo chant in response to the choir. Later it became a motet based on a free theme, with the alternation of solos (polyphony) and chorus (homophony).

In 200 S. Clemente d'Alessandria affirmed as the only genus suitable to exalt the divinity by singing, the *diatonic* genus. The *cromatic,* which included the use of minor values and eighth notes (to give the impression of color) was relegated to courtesan songs. In this way the war of the Church Fathers against chromatism begins.

In Egypt appropriate hymns were sung according to the different liturgical circumstances. Deacons, clerics and the people took part in these songs during the Roman imperial persecution. With the edict of Constantine, the freedom of worship was recognized to Christians: musical experiences that had remained obscure for three centuries came to light.

In Antioch in the first half of the fourth century, Flaviano and Diodoro ordered the choir psalmody in which two half-choirs, one male and the other composed of women and children, alternated to then sing the recovery together. This execution was called *antiphonie* (the singing voices were distanced by an octave). The *psalmody* consisted of the syllabic recitation of the text in the melodic range of a few intervals. Despite the musical poverty it redeemed itself in the greater wealth of the hymn. The *Innodia* dealt with extra-biblical texts, it was built according to the tonic accent in iambic meters.

At the beginning of the fourth century the liturgical choral of the various Christian churches of the East was ripe for expansion throughout the Mediterranean world where it met and was influenced by other musical statements of Christianity. The word choir thus assumes the modern meaning of *multitudo in sacris collecta* enunciated by Isidore of Seville.

With S. Ambrogio (diocese of Milan, 374 - 394) the new choral ethos takes on value and political strength. According to many scholars, he was also the author of many music considered fundamental by the Catholic Church.

With the development of liturgical choralism we witness the development of sacred architecture, Christian basilicas become symbolic cities of God whose interiors are adapted for liturgical representations with raised choral spaces (this can be seen in most of the Byzantine style churches). In this period groups of educated singers are formed to whom the execution of liturgical songs is committed; these groups took the name of *chorus*.

In Rome, since the time immediately following the edict of Constantine, Pope Damasus I designed the first *schola lectorum*. The first true and proper arrangement of all Christian liturgical chorality took place in the East with Justinian. Even before his accession to the throne, the choral liturgy was in great and luxuriant flowering. The emperor took care of the musical organization of the cult: he fixed the number of singers for each church; the choir was to take the model of the Western *Scholae Cantorum* and their function was to guide readers and the singing community. St. Gregory the Great transformed the *Scholae lectorum* into *Scholae Cantorum*, which became true seminars aggregated to the basilicas of St. Peter and St. John Lateran. The Church of Rome imposed not only forms of worship but also Roman or Gregorian chant. Gregory the Great began to remove the office of cantor from deacons to give it to clerics of lower rank and to subdeacons; these became the fulcrum of the new choir. Children with a good voice could be admitted to the Schola where they received a complete education in the field of the seven liberal arts, with particular emphasis on musical education. The duration of the studies was nine years: from *Puer cantus* to cantore. The *Pueri cantus* were under the direction of four *paraphonists*, most skilled singers (the first was the choir director and had only the abbot above him). With the improvement of the ordinances, Christian chorality becomes more and more professional; the initial appearance of *Chorus laudantium* is lacking and it uses complexes that are always better trained and of small numbers. The solo style takes over.

From polyphony to the a cappalla choir

In the twelfth century there was a remarkable evolution in the structuring of the choir: besides being able to be admitted also lay elements could be part of the choral formations even those who did not come from the *Scholae Cantorum*; we start talking about *chours virili* and *chorus matronalis*.

The *Ars Nova* compositions tend to give greater importance and sonorous thickness to the upper part of the *cantus* (in polyphonic music it indicates the upper extreme part) to the detriment of the *tenor* and the *vox organalis*.

In central Italy in the 12th and 13th centuries there was a manifestation of popular chorality with the *Franciscan Laude* who had a monodic course and a strophic structure. This succeeded in transforming the aulic and subjective elements of the lyric lyric poetry into popular and collective. The secular companies of *laudantes* turned into brotherhoods anticipated some aspects of modern choral societies and contributed to the rise of the first example of choral poetry in Christian Europe. The polyphony took on a choral character only in the fifteenth century.

In the 14th century the *musical chapel* (originally indicated that part of the church where musicians and singers were gathered for performing vocal music without instrumental support) had a reorganization influenced by the French musical costume of the time. Pope Sixtus IV created the Sistine Chapel and in 1480 he laid the foundations for the creation of Giulia Chapel (work of Giulio II), made up of twelve singers.

The King of Bohemia Charles IV, in the 14th century, organized choral singing along the lines of papal musical chapels in the cathedral of Prague. In the first half of the fifteenth century Polish musicians established relationships with Franco-Flemish musicians working in the Italian musical chapels and brought new choral experiences to court.

With Giovanni Ockeghem the concept of "choral composition" acquires a precise and definitive meaning. Four-part polyphonic writing is affirmed. In addition to setting the number of singers at twelve, Ockeghem oversaw the choice of voices for the musical chapel he directed. With Josquin Des Prés and Orlando di Lasso, between the sixteenth and seventeenth centuries, one arrives at the masterpieces of Italian polyphony. The terms *musical chapel* and a *chapel style* are defined: the first indicates the meeting place of the choirs, the second refers to the way of making polyphonic vocal music without instrumental support or accompaniment. At the time of Palestrina, in the musical chapel of the most important Roman Basilicas, the *cantores* were sixteen or eighteen including the three or four *pueri cantores* which were entrusted with the part of the *cantus*. With th term *Roman choir* or *Palestrina choir* we refer to a *chapel choir*.

In France and Germany, the accompanied monody, instrumentality and concertante style were imposed. In Germany the figure of the *Kappellmeister* was created, which corresponds to the modern master conductor and concertmaster. In Italy the popular chorality developed.

The chorus of mass

Towards the end of the Middle Ages the melodies of the *Ordinarium* were introduced into the sung mass: fixed texts that resumed the antiphonic or responsorial monodic practice. The *praecentor* performed the intonation of a few notes and followed by the antiphonal alternation of the two semi-choirs that met at the end. The Mass sung during the first period of polyphony and throughout the time of the *French Ars Antiqua* (XII - XIII century) was characterized by the invariability of the texts and the vagueness of the patterns. With the *French Ars Nova* (XIV century) the five parts of the *Ordinarium* were composed on a single *tenor*.

From the beginning the Mass was essentially a choral practice until the accompanied monody and instrumentality in the seventeenth century took over: the instruments began to oppose each other and to dialogue with the choir. The solo parts began to emerge: first four then three and finally one voice. The harmony replaced the polyphony, the tones with the modes. In 1773 with Bach's *“Mass in B minor”* the perfect balance of the musical elements that flowed into the Mass took place. In this period the custom of separating the parts of the composition is developed to be used for different executions. In the 18th century compositions, the chorus was given the function of harmonious and coloristic support for the solo (this can also be seen in Haydn and Mozart). Beethoven, on the other hand, thought that church music should only be performed by voices. Mass is increasingly becoming a dramatic composition, written for solemn circumstances and for less religious worldly purposes. With Beethoven we notice an evolution of the musical language, while Shubert continues to refuse to set the credo to music.

In the authors of this period the search for an image, an attitude, moods and choral expressions is insinuated that, if pursued by the genius, are welded together in a collective prayer or song, while, brought to the system, they cannot that fall into rhetoric and the academic. Against this decadence arose men of art, music and letters, lay and religious. In Italy the movement for the revolution was promoted by magazines and periodicals and had musicians such as Tebaldini and Bossi as promoters. This movement also had an international resonance to the point that in 1903 Pius X established the document *Moto Proprio* in which Gregorian chant and Palestrinian polyphony are cited as perfect models. However, this leads to the development of an incredible number of *pastiches* of Renaissance Masses. The *Motu Proprio* brought the choral spirit back into sacred music, incited musicians to the austerity of religious accents, to the essentiality of means.

Renaissance and Baroque

Towards the end of the 1500s, with the adoption of dialogue texts, the madrigal started to become representative. In the second half of the century, with the abandonment of the contrapuntal technique and the affirmation of the harmonic one, it frees itself from its medieval aspects and from the mottettistiche descendants.

During the Renaissance the concept of choir takes on a new meaning, indicating any sound formation with a strong uniqueness of timbre. The concepts of *chorus vocalis* and *chorus strumentalis* arose. In this period the technique of *cori spezzati* developed, in which there is a return to the ancient antiphonal principle.

The practice of choral opposition translates into music the ideal of contrast, typical of the Baroque. In the last decade of the 16th century the *Continuous Bass* was born with which the vertical harmonic style came to light. Since then the ecclesiastical sung music is divided into solo and choral literature.

Reformation and Counter Reformation – Corale and Laude

The religious movement of the sixteenth century had much influence on music and in particular on choral music. Martin Luther, along with other reformers, understood the importance of this art and the profit that could be drawn from it. In the new worship the whole community will be able to sing psalms and canticles to express their hope and gratitude towards God. For this reason, the songs had to be simple and easy as well as having to be written in the spoken language. The song was no longer confined to places of worship but also expanded among the domestic walls, during work, meetings and in other circumstances. In these circumstances the song was structured in several voices: The *Corale* was born (musical expression typical of the Protestant cult). The repertoire included spiritual songs from the Middle Ages, Latin hymns, parodies of profane songs, ballets by Giovanni Gastoldi and Flemish melodies. From these songs Bach realized the *Corali*.

Luther took a personal interest in the organization of choral groups and was responsible for instituting groups of young students who were taught new choral prayers.

The public school had the task of spreading the chorality. Already in the Middle Ages there were choirs of pupils but only in this period was he given such importance.

Catholicism implemented a counter-reform against Protestantism. Between 1562 and 1563, with the Council of Trent, the exclusion of choral polyphony in cult practices was proposed to return to the pure and simple Gregorian monody. Sacred music was accused of the artificiality of vocal counterpoints and worldliness during performances; for this reason, the Catholic chorality had to carry out an expressive purification. In Rome, S. Filippo Neri structured the choirs in three parts, left the music unchanged and replaced the profane words with more spiritual ones: *laudi* developed. The mass of the faithful performed two *laudi* interposed by a *sermon of edification*, held by one of the fathers of the Congregation. The *laudes* became the strophic religious and popular songs of the Umbrian and Franciscan *lauda* where they alternated choir and soloist. In the 16th century they became polyphonic and isorhythmic arias whose content was initially meditative and exhortative. The Filipino laude, with the introduction of dialogue texts and new monodic style music, evolved towards a representative form of outlet.

The choir in melodramma and in the music of representative style

In February and October 1600 there are two very important events in the history of music: the birth of the *oratory* and *melodrama*. Furthermore, interest in the individuality of the song develops with the consequent search for musical expressions characterized by lyricism and drama. There was no lack of opposition that encouraged a return to polyphony. There was a flowering of S*piritual Madrigals* and collections of *lauds* commissioned by other illustrious masters (therefore not taken from the anonymous repertoire). The opponents of polyphony supported the return to the ideals of music and theater of ancient Greece. Modern musical and representative forms were born; the choir had to proceed to a slow downsizing and re-propose a new state of necessity.

In Germany, with the *Gluck Reform* the Choir wasbrought back to the function it had in the Greek tragedy with the diversity which, in this case, was the only musical element. When the melodrama ceased to be courtly the paying bourgeoisie began to attend the shows; in this context the choir took on accessory and decorative tasks until it was eliminated (as it was not requested by the public). With the Gluckista reform, however, the choir enters becomes a necessary element of the drama.

At the beginning of the 600s, the Roman school was the one that gave the choir the most importance. In the oratory the choir remained an essential constructive element. Derived from the *lauda* it took the name of *historia* when the Latin text denounced the origins of the motetto. After the composer Giacomo Carissimi the choir disappeared from h*istoria*. The choir became less important due to the nascent instrumentality; the narrative role was limited and was replaced by soloists of the historian. The choir in the Neapolitan and Venetian oratory was relegated only to the final part.

In Germany the oratory gave the choir the fullness of musical weight. With Haendel and Bach the chorus summarizes importance. In the cantatas of the latter one must distinguish between *choral* and *chor*: the first indicates the simple melody harmonized to four parts that the choir sings accompanied by obligatory and concertante instruments; the second indicates large movements and massive polyphonic constructions with several voices.

In the English *cantatas* of the Baroque period the Anthem had great importance: religious songs arose around 1600 as an adaptation of the Catholic motive to the Anglican cult.

The choirs of this period were never too numerous.

In the eighteenth century in Italy, France and Germany we tend to write with an instrumental or vocally soloistic sensitivity. During the Enlightenment the choir dried up in academic exercises (sacred and profane).

From the French Revolution to the present day

In 1795 the choir played a social political role: the French politician La Revelliere-Lepeaux proposed to the Convention to celebrate national holidays with universal choirs.

The nineteenth century, in Europe, is the century of music: with the birth of national schools the popular favor for this art begins to be manifested. The choir in the symphonic structures refers to a concertante style, based on the previous experience of oratorio and cantata. In Haydn we find the best balance between choir, solo and orchestra.

With the revaluation of the *Bach* production carried out by the German Romantics, many choral *Lieder* were produced, with mixed and even voices; harmonic writing and expressive resources were enriched.

At the beginning of the 19th century in France the theater choir accentuates its participation in the drama. In Paris, Gluck's reforming theories prevailed. There is a coralisation of the opera, especially in Paris and to a lesser extent also in Vienna. With the accentuation of the formative characteristics of the Grand-Opera, however, the choir begins to lose the dramatic and musical essentiality that it had conquered in the last gluckist and post-gluckist works.

In Italy, in the first half of the nineteenth century, oratorical choral music resumed the Rossini model and the gluckist model imported by *Mayr*. The choir still retains a dramatic and musical importance that brings it closer to the rank of protagonist. The choral opera model had something archaic, classical in it, and there was also a difficulty in implementation: there were few theaters that had the choral and scenic means for the staging of such works. In Italy a network of minor theaters full of lyrical and ambitious seasons of newness was spreading that did not point to the constant presence of a large choir.

Verdi approaches the romantic model of the opera with characters. The choir, in this case, remains an element of high musical decor. In the first part of the first act of *Othello* there is a development of choral writing so that the choir is also inserted into the action. Post-Verdi Italian opera will rarely reach such a high choral appearance. Verdi's students become representatives of the verist current: in some the choir takes on the role of protagonist of scenes or prologues.

Ildebrando Pizzetti has given back to the chorus a noble and essential function in the Italian musical theater, bringing back the writing to the ways of a true vocal polyphony of Renaissance tradition. *Don Lorenzo Perosi* also stands out, thanks to which the choir returns to its maximum splendor.

In Germany, Carlo Maria Weber starts German musical theater. In his works the choir portrays scenes of character and picturesque. The culmination of the great German romantic arc is the choral one of Riccardo Wagner; in his latest work, the *Parsifal*, the choral as well as reliving the spirit of the sixteenth-century polyphony, reveals a novelty of harmonic connections and chromatic treatments destined to open new possibilities to the use of voices in chorus.

In Russian opera there is talk of choral works in which there is the participation of historically qualified masses in the action and passions of drama. The sense of dramatic realism is due to the scenic language and the ethnic element. In his early days Russian choral music had contacts with Italian culture through Massimo Berezowkij and Dimitri Bortnianskiy.

In Italy Gianfrancesco Malipiero takes up the musical sensibility of the Renaissance and the Baroque. In his works the choir takes up the concertante Baroque style of the Venetian school of the ‘500-‘ 600.

In the languages of the 1900s motettismo, madrigalismo (‘500) and the spirit of the oratory (Barocco) are taken up again. A movement of revaluation of the choir developed.

In America, in addition to developing the coralism of *Spirituals*, new expressive possibilities have been acquired such as the use of the effect of the closed mouth, special vocalic and phonetic emissions on onomatopoeic syllables (impressionistic music) and spoken chorus (expressionist).

In all the production of the modern Viennese school, we owe the beginning and use of the dodecaphonic system, there is a keen interest in the choir whether alone or used in concertante form.

Organization and dissemination of choral singing

With Romanticism, a philosophical and pedagogical trend developed in Germany and Switzerland, which in Fichte found the apostle of chorality as the idealistic symbol of the unity of the German nation and in the Swiss Pestalozzi the adherent of the function of choral singing as a means of education popular.

The nineteenth century is a century of awakening choral music in every European country. In France there is *Orphéon*: a choral projection of the ideals of democracy derived from the French Revolution. In the 1800s, it indicated a movement to promote and unite initially only male choral societies. The first male orfeonic societies arose in Paris in 1821; in 1848 the *Union Chorale* and *Les Enfants de Lutèce* were established; in 1860 the *Academie de chant* and *La Concorde* were born in Strasbourg. These societies were characterized by evening courses and paying choristers with the objective of forming large choral organisms. This movement created a repertoire for four male voices. This movement was also transplanted in northern Italy. After the two world wars new taste requirements arose, the orientations tended to be more professional and selective, no longer prone to the large masses, for these reasons the orfeonic activity ceased almost completely both in France and in Italy.

In 1907 Pierre Martin formed the *"Les Petits Chanteurs à la Croix de bois"*: the little singers formed a kind of flying chapel (they were not linked to any basilica or seminary). This idea also developed in other centers and this led to the foundation of the "International Federation of Little Singers": Little singers who train themselves in music and choir singing in a repertoire taken from the best polyphonic tradition.

Mass choirs developed in Germany. Northern Germany was heavily influenced by Zelter, founder and promoter of choral associations as well as *Liedertafel* (a non-profit choral association). Initially made up only of men, in recent times women are also being admitted. This made possible the establishment of a repertoire comprising music from Bach to Mahler. All this was also emphasized by the radio which proposed the broadcasting of recordings of qualified groups.

In Switzerland, thanks also to Calvinism, a true and proper choral mentality was created. *Pestalozzi* and *Nageli* found a prepared environment that led Switzerland to a leading position in the life of the choir (especially the male). Only in 1910 was the association of mixed singers created.

In England choral music began to develop with the Reformation. From the time of Purcell and Haendel choral festivals were organized: the *Three Choir Festival* in which the choirs of the cathedrals of Gloucester, Worcester, Hereford took part in 1724. In 1927 the *Royal School of Church Music* was founded which had the task of renewing ecclesiastical music. Performances of choral music are also carried out through the numerous lay associations (in London: Royal Albert Hall Society, Choir J. S. Bach, Choir Philarmonic, choir of B.B.C.) and national and international festivals; among the most important there is that of Llangollen (North Wales), a region where each village contributes to maintaining a tradition with deep historical roots. The English choral repertoire ranges from the works of *Haendel* and *Bach* to the polyphony of the ‘500-‘ 600, without missing modern music.

If in England the flourishing choirs are those linked to the cathedrals, in other areas there are secular correspondents: in Canada we find the university choirs dedicated to the oratory and the a cappella choir; in Australia instead there are the choral groups of the Melbourne Conservatory, of the University of Sydney, of Adelaide, Brisbane and Perth. In Ireland we find the same choral situation in Wales. In Belgium we find the choral groups of the *Philarmoniaue* and the *Concerts spirituels* (Brussels), Cecilia in Antwerp and others developed in various parts of Belgium. In Holland we find the *Palestrinakoor* in Utrecht, Tookunst in Amsterdam. In the Scandinavian countries and Finland, instead, there are choral societies of workers, bourgeois and students. In Czechoslovakia we find bass voices that have an exceptional extension and volume (like the Slavic basses). Along with the other Slavic countries, there is also a passion for the choral competition. In Greece, at the theater of Delfo, an attempt is made to reconstruct the chorus of the ancient tragedy. In Russia, music and choral singing are considered fundamental elements of popular education; singing is present as a compulsory subject in all schools. This development of the choir in Russia has deep historical roots. In 988 the clergy of the Greek church brought to Russia the monodic chant which partly took up ancient rhythmic and modal inflections. In Poland, the choral movement has developed today in the worker and peasant environment. Amateur societies draw from the repertoire of folklore.

In the United States choral music began in 1774 with the founding of the *Collegium Musicum* of Bethlehem (Pennsylvania) by a group of Moravian immigrants. In 1768 the *Musical Society* of Stoughton was created: organized by Billings for the execution of the classical orators it became the model of the great choral societies that developed in the USA during the XIX century. Beyond the Glee-Clubs, society of amateurs specialized in popular singing, great choral groupings of a professional nature are developed; we also find the choirs of the various universities such as Harward, Yale, Princetown, Columbia, Cornell, Rochester. Of note, there are also the small vocal polyphonic formations that refer to the singing of the *Spirituals* (for example *The Platter*): in them we find the religious fervor of the American negroes who jazzily transformed the original elements of the Lutheran choirs imported by the first settlers Anglo-Saxon.

In Italy it resents not having considered choral singing as an irreplaceable element of social and civil formation in every school order. Nevertheless, there is fertile ground for musical ferment, choirs, beautiful voices and enthusiasms. In Turin in 1875 the *Academy of Choral Singing* was born; subsequently other orfeonic ones also developed in other cities. These centers hold out better in those cities where there is a craft economy. During fascism there was an example of rural chorality with the Canterini Romagnoli, whose comrades prospered in almost all the towns of Romagna. The Roman Polyphonic Society directed by Monsignor Raffaele Casimiri gained worldwide fame. Domenica Alaleona contrasted the most demagogic aspects of the Orponic choral, favoring the rebirth of interest in the vocal polyphony of the Renaissance and Baroque periods. The Arezzo International Choral Festival was also very successful, and amateurs from each country can participate. Romeo Bartoli founded the *Camerata Milanese del Madrigale*; the repertoire was based on the authors of Renaissance and Baroque vocal polyphony. Among the professional groups the Cori Stabili of the theaters must be mentioned; moreover, the Chorus of Turin and the Piccolo Coro Polifonico of Turin, the Choir of Milan, of Rome and the Small Polyphonic Choir of Rome and, finally, the Choir of the "A. Scarlatti" of Naples. Some musicians strive to give choralism a foundation and a didactic diffusion (example of Achille Schinelli). Despite these choral developments, in Italy, there is still no conviction that the active exercise of choral singing has a strong formative power of the social and moral sense of every citizen.

2.3 Choral Sound

(11) According to *Daugherty* the choral sound consists of the following characteristics:

1. It has the property of both complex sounds and very narrow band noise;
2. The sound character corresponds to the sum of sounds that are similar but not coherent in phase;
3. It has a spectral peak in the 500-700Hz region (using long-term average spectra);
4. The SPL (sound pressure level) of choral sound has ample short-term random variations due to the beats.

The so-called choral effect occurs when many voices and their reflections create an almost random sound of such complexity that the normal mechanisms of localization and auditory fusion are interrupted. The sound is dissociated from its sources and has an independent existence. In the choral sound the whole is more than the sum of its parts. The instability of the fundamental frequency can produce *flutter* or fluctuations of the fundamental that do not influence the pitch but can alter the timbre of the sound.

According to *Hunt* the unity, the attractiveness, of the choral vowel (essential for the perception of fusion) mainly concerns a question of articulatory intonation.

By analyzing the recordings of professional choirs you can see the properties listed below:

- Major thirds are larger singers of equal temperament (quite large yields) (12);
- Minor thirds are sung more narrowly;

- The octaves and fifths are sung more closely to the simple intonation (*Lottermoser* and *Meyer*).

According to the authors *Lottermoser* and *Meyer* the first two points serve to increase the contrast between the major and minor key of the chords (12).

From the results of the studies conducted by *Ternstrom* we note a greater masking of the own voice at low frequencies. As reported by *Tonkinson* choral singers use the Lombard effect: in the presence of a masking sound they increase the intensity of their voice to listen to themselves.

Referring to the studies conducted by *Ternstrom* regarding the *SOR* parameter (see chapter 3) in choral environment there is a spectral distortion in the feedback received from one's voice as one's voice is lower in our ears. This is due to the fact that the low frequencies diffuse more with respect to the high frequencies, which having a longer wavelength tend to go straight. If the sound of the choral reference is greater than 5dB compared to the feedback of one's voice, the intonation errors increase significantly.

In the choral sound it is very important to listen to one's own voice as this would be able to correct the deviations of the vowels that possess an intrinsic intonation (12). Beacause *feedback* can be masked in choral singing, this intrinsic intonation of the vowels would lead to intonation problems. The accuracy of the intonation may depend on different sound properties: feedback volume in relation to the reference, the prominence of the sound and the general shape of the spectrum. These characteristics depend both on the acoustics of the room (reverberation time, spectral bias of the reverberation, spacing between the singers) and the vocal behavior of the singers (12).

The firtst component, the room acoustics, can influence the following factors (11)

1. Level with which the singers listen to the rest of the choir;
2. Intonation of the single singer (depending on how strong he can hear his voice)

The sound reflected in a room can be divided into two parts:

1. *Initial reflections*: reflections that arrive within 50-100ms and are generated by reflective sound surfaces in the vicinity of the choir.
2. *Reverberated sound*: Continuous sound of increasing level after the initial reflections.

The research carried out by *Marshall* and *Meyer* in 1985 with ensemble singers reported a greater appreciation of lateral reflections than vertical ones (especially if the level of late reflections was high). Regardless of the reverberation time, the singers preferred early reflections in the time interval between 15 and 35ms (ie reflective walls placed at a distance between 2.5 and 6m). The first reflections that arrived with a delay of 40ms (6.5m) were unpleasant (12). The choirs tend to adapt their sound level and the use of their voice to the acoustics of the room: for example in more absorbent rooms, they tend to use a higher laryngeal position.

2.3.1 Comparison between choral and solo singing

(4) In choral singing individual voices should not be distinguishable as such. The choir singers need to get a mixture of their own voice with that of others. For this reason the singers of the choir, in addition to following the music should strive to make the sound of their own voice similar to that prevalent in the group. From the acoustic point of view this could imply three combinations:

- Loudness;
- Forming Structure;
- Vocal source properties.

Rossing et al. they compared solo and choral singing. From the results it was noticed that the professionals tend to modify their voices passing from one way to another to sing: in choral mode the formant of the singer was less prominent and, therefore, the amplitude of the fundamental was higher (articulation similar to that of the speech).

Since between the choir and the soloist the use of the voice is quite different, there are two very different modes of musical performance. In the first case there is an emphasis on fundamental tones instead of partial ones. This is achieved through adjustments both in the articulation (regulation of the forming frequencies) and in the phonation (change in the glottal waveform). *Ford* has noticed in some subjects (university students) a prevalence for the non-resonant choral tone, that is, without forming the singer. Another peculiarity of choral singing is that there are frequent adjustments in intensity; subjects, usually, tend to adjust their levels to those of other singers (in solo mode, however, the level depends much less on that of the accompaniment). In this regard, *Goodwin* noted that sopranos use a softer voice and weaker partials when they have to sing in a choir (hence when voicing is required). The solo singers, on the other hand, sing more powerfully in the region of the singer's formant, using a reduced distance between the third and fifth formant (11). This difference in spacing reflects the articulatory differences between the two ways of singing.

Goodwin, studying choral fusion among sopranos in various ensembles, discovered that when they tried to blend their voices they produced tones with a lower sound pressure level than solo singing. For example, female singers sang at a higher sound pressure level in solo mode than when they tried to get a choral mix. In choral singing the forming frequencies were essentially the same but those of the second and third formants were produced at a reduced level. A reduced vocal effort implies a slope of the steeper source spectrum.

In conclusions we can say that in the solo song the formant of the singer is prominent and the breadth of the fundamental tends to be less dominant. The reason for this difference may be associated with the fact that in choral singing the sound pressure level depends on the general level of the choir, so the level average tends to be smaller. An increase in the vocal volume is normally associated with a lower slope of the spectral envelope in all voices.

(13) *Sundberg* has done research to verify that the singer's formant is not used by the choir singers. The experiment was carried out with Western opera singers of classical training. The singers of the opera choir have an increase in energy in the frequency range (called formante of the singer) that can be translated into a richer sound quality and a greater dynamic.

In the paper *"The Acoustic Characteristics Of Professional Opera Singers Performing In Chorus Versus Solo Mode"*, the authors found substantial differences both with regard to the *SPR* parameter (*Sound Power Ratio*, difference between peak levels in the low range, 0-2kHz, and in the high range, 2-4kHz, of the spectrum) and in the parameter *ER* (the total energy balance between the low and high ranges of the spectrum): for many members of the Opera choir, in choral mode compared to the solo one, there is a high relative energy in the high frequency range (interval in which the formant of the singer appears).

Nordenburg and *Sundberg* have verified that with an overall increase in *SPL*, the *ER* and *SPR* parameters decrease when the slope of the voice spectrum changes with vocal effort. This is in contrast to what was found in the previous research in which, during the choral performance, less energy was found in the region of the singer's formant. *Letowski et al* describe a particular phenomenon, present in this mode, so that inexperienced singers tend to use a brighter vocal quality while trained ones tend to dampen their own voice (this was done, in fact, to obtain the choral mixture). In this case, however, the individual singers kept the energy in the singer's forming area constant or increased: in this way the operatic choir produced a stronger and fuller sound that allowed it to be heard compared to the orchestra. Despite this, however, the effect of choral fusion was had.

In conclusion it can be stated that the requested singing method in an opera choir requires the possibility of using a vocal timbre similar to that of solo singing.

2.4 POSITIONING OF THE SINGERS

The arrangement of the choir can be determined taking into account some factors (5).

Positioning of the singers within the vocal section: In this field there are different philosophies. Some directors prefer to place singers with similar timbres and volumes close to each other; others, instead, prefer to alternate different timbres to improve the vocal fusion. Placing singers with similar neighboring tones provokes a difficulty in being able to listen to the voices of the other sections (this could be a problem and cause repercussions in intonation and dynamic balance).

Formation: term that indicates the way in which the vocal sections are organized. Literature tends to take into account the height of the singers so that everyone can see the choir director.

Spacing: This parameter influences the volume a chorister produces in relation to the rest of the choir. There are some volume balances that can be favorable for choral singers based on the surrounding space.

2.4.1 Formation

Jers highlighted the advantages and disadvantages of three types of formations (5).

Formation	Pros	Cons	Pattern
Block Sectional	The sound is stronger than the *"Column Sectional"* formation. It can be used for polyphonic works.	Singers at the edge of the vocal section may have difficulty listening to other singers in their group. Singers in the middle, on the other hand, may have problems listening to their own voice compared to others.	SSSAAATTTBBB SSSAAATTTBBB SSSAAATTTBBB SSSAAATTTBBB Conductor
Column Sectional	Suitable for homophonic music; clarity of the voices and good vocal balance of the different sections.	Some sections will be more distant than others.	TTTTTTBBBBBB TTTTTTBBBBBB SSSSSSAAAAAA SSSSSSAAAAAA Conductor
Mixed Formation (SATB quartet)	The voices reach the audience in a better fusion and often seem stronger. For the singers it is easy to listen to the other sections; this improves the intonation	The singer can feel alone. The conductor may have difficulty directing the individual sections.	SATBSATBSATB BTASBTASBTAS SATBSATBSATB BTASBTASBTAS Conductor

Table 9 Pros and cons of formations studied by Jers: Block Sectional, Column Sectional and Mixed Formation. The last column shows the diagrams related to the formations

In *"Select Acoustic and Perceptual Measures of Choral Formation"* (14) this three choral formations were compared on an acoustic level. The research was carried out with the participation of a choir composed of 30 expert choristers (18 females and 12 males).

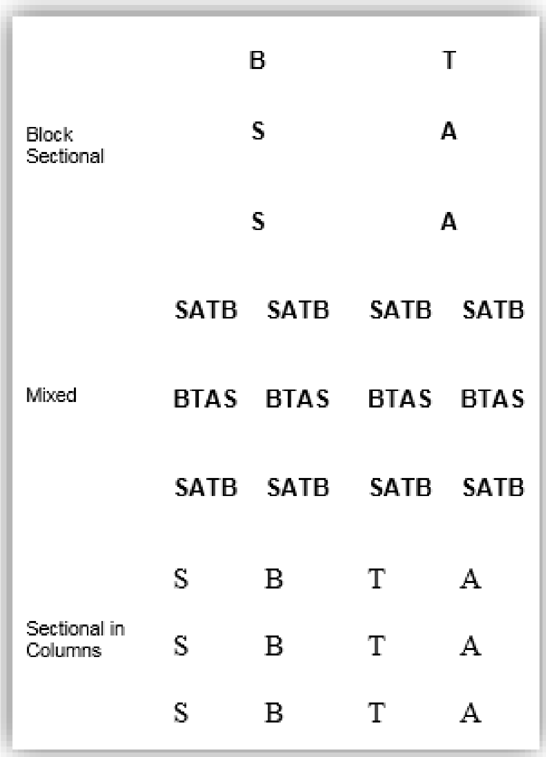


Figure 5 Vocal Parts formation schemes

Block sectional: the singers are arranged in three rows. In the two front rows there are the sopranos to the left of the conductor and the high to the right; in the last row, on the other hand, the bass on the left and the tenors on the right.

Mixed Formation: the singers are arranged in quartets (always on three rows) containing a soprano, a high, a tenor and a bass.

Sectional in columns: each vocal part must be next to each other; the sopranos and basses are placed on the left while the highs and tenors are on the right of the conductor.

Each formation showed the maximum energy in the 500-600Hz band interval, followed by a decrease up to 2-3kHz in which an increase of about 5dB of energy was observed. This energy is not so high as to be considered formant of the singer.

Choral Formation	Vocal Part (N)	Ease of Production	Sound of Choir	Ease of Blending With Section	Ease of Hearing Others	Prefer Singing
Block						
	Soprano (8)	8.07 (2.10)	7.08 (1.61)	6.76 (3.04)	5.78 (2.61)	5.89 (2.18)
	Alto (10)	8.13 (1.83)	7.10 (1.88)	8.39 (1.71)	5.75 (2.30)	6.20 (2.76)
	Tenor (5)	8.77 (1.06)	6.05 (2.88)	6.71 (3.45)	5.23 (4.16)	6.22 (3.56)
	Bass (7)	7.99 (1.42)	6.80 (1.70)	7.62 (1.62)	5.83 (1.83)	6.63 (1.55)
Mixed						
	Soprano (8)	5.28 (2.60)	7.69 (2.22)	6.00 (2.89)	7.10 (3.52)	7.21 (3.35)
	Alto (10)	7.23 (2.55)	6.80 (2.34)	6.20 (2.93)	9.20 (0.73)	8.68 (1.60)
	Tenor (5)	6.42 (3.52)	6.51 (3.64)	6.05 (3.34)	8.13 (3.88)	7.09 (3.77)
	Bass (7)	5.01 (1.94)	6.26 (3.38)	2.82 (2.58)	8.63 (1.60)	6.94 (3.43)
Column						
	Soprano (8)	6.81 (2.99)	4.08 (2.13)	5.78 (3.40)	2.39 (2.20)	3.73 (3.88)
	Alto (10)	7.56 (2.38)	5.68 (1.69)	7.18 (2.18)	4.80 (2.78)	4.55 (2.61)
	Tenor (5)	8.38 (1.6)	7.81 (1.96)	8.68 (2.33)	6.22 (3.21)	6.57 (3.91)
	Bass (7)	9.64 (0.23)	8.66 (1.62)	9.36 (0.75)	6.04 (2.74)	8.66 (0.97)

Figure 6 Preferences about formationa and vocal part

From the image shown above we can underline the following results:

- *Ease of production* The Sopranos, Alto and the Tenors preferred the formation of blocks, the Basses, instead, the formation of columns.

- *Sound of Choir* The Sopranos preferred the mixed formation, Alto the block sectional while Tenors and Bass the formation in columns.
- *Ease of Blending with section* Sopranos and Alto ones preferred the formation in blocks, while Tenors and Basses the one in columns.
- *Ease of hearing Others* Everyone preferred mixed formation.
- *Singing* Sopranos, Altos and Tenors preferred the formation of blocks while the Basses ones the columns formation.

Generally, it can be seen that Sopranos and Alto have similar preferences: block and mixed formation compared to column formation.

(11) From empirical surveys carried out by *Lambson*, *Tocheff*, *Aspaas et al*, *Daugherty* and *Ekholm* we note that, with regard to the formation of the choir, among listeners there are no significant preferences while among the choristers the following considerations can be found:

- The weak singers prefer the formation in section;
- Stronger female singers prefer mixed formation;
- Male choristers prefer to sing in the central section of the choir;
- The strongest singers prefer the outer edge.

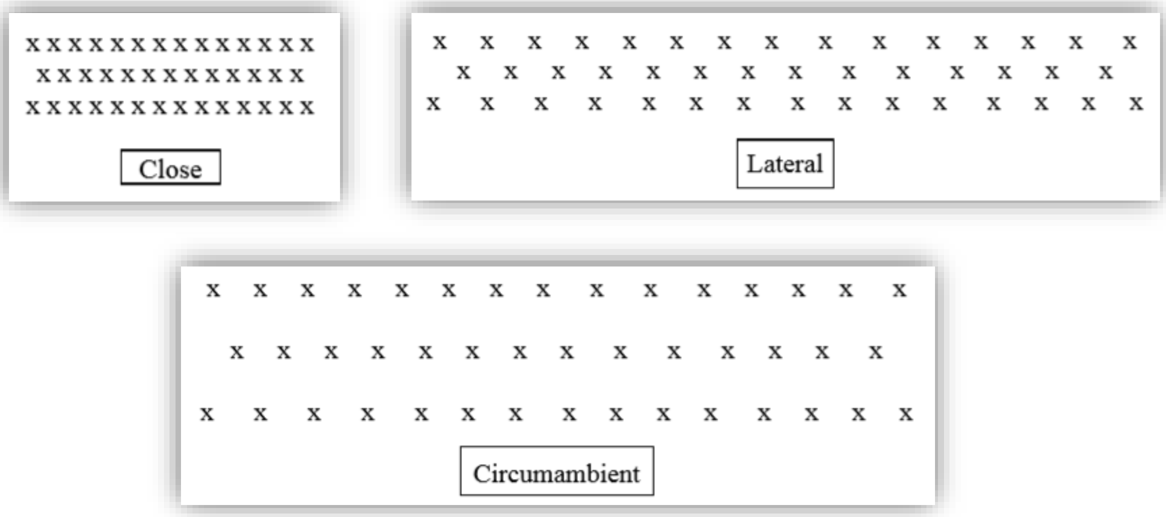
According to *Daugherty* these preferences are linked more than anything to spacing and not to formation. From the studies conducted by *Aspaas et al*, however, no spectral differences were found in the sound due to the formation.

2.4.2 Spacing

The issues associated with chorus spacing and choral sound as well as having physical meanings also have metaphysical dimensions (15).

Physical Dimension

Daugherty determined the following choral spacing (11).



According to the author, the spacing has a positive influence: there is a better vocal production as well as being able to listen better to oneself and the whole. Listeners prefer a widespread spacing for sectional formations, while a less extensive spacing for mixed formations. Weak singers prefer lateral or narrow spacing, while medium and strong singers tend to prefer circumambient or lateral spacing.

From the experiment conducted by *Daugherty* with a twenty-person chamber choir, the following preferences were noted: male singers (tenors and basses) preferred lateral spacing, while female singers (sopranos and highs) spaced out circumambient.

The preference for a certain spacing can also be found with the work done by *Ternstrom* regarding the *SOR* parameter and therefore the balance between the sound of the *"Self"* (one's own voice) and *"Other"* (the rest of the choir).

Pedagogical Implications

This dimension refers to how the choirs present their best sound. Widespread spacing can be a means of developing a more independent sense of singing in choristers, a better balance between one's own voice and the sound of the entire choir, as well as a better production of choral sound. Naturally, the singers and the places for the performances are different from time to time, which is why it is difficult to generalize the results deriving from a specific performance. In this regard, *Coleman* found that individual singers within the same choir can vary greatly in their vocal output power, although they may be subject to the same choral training. Allowing the singers to assist in the process of experimenting with spacing by making them also make assessments and making them express their preferences focuses their attention on the nuances of the choral sound and allows them to have greater mastery of the choral sound on the whole.

According to *Ehmann* the choral concerts should employ a variety of choral formations sensitive to the musical structures of the compositions that are being sung; a similar principle can also be applied to the spacing of the choir and to the various compositions.

Informal experimentation with choir spacing can have valuable pedagogical results useful for the following reasons

- Introduction and awareness of choristers on the fundamental questions of choral sound;
- Grant the singers greater ownership of their choral sound;
- Discouraging over-exploitation and improper use of the vocal apparatus as the singers are able to find a comfortable and natural balance between the sound of feedback of their voices and the reference sound of the choir as a whole;
- Sing in a balanced way

The chorus spacing, ultimately, can add desirable nuances to the choral sound of a particular ensemble (contributes to the difference between pleasing or less choral sound).

Philosophical Dimension

A problem that could compromise a good spacing could be the lack of space.

In history, choral music was deeply associated with the functions of social, religious and dramatic space. The Greek choir performed in large circles. The choristers of ancient Israel were positioned in various ways: seated, standing, high, not elevated (*Keiling*). In the Middle Ages, Christian singers often moved in the exhibition space (*Helmrich*). Particular the "*cori spezzati*" ("spaced choruses" of the Venetian Renaissance), which were based not only on elements present in the Jewish antiphonal chant, but also on the more innovative elements of the 20th century, as in the case of "The Lake" by Alvin Curran: composition designed for a mixed choir of fifty voices to be performed on the boat (five or six choristers per boat). The singers performed while rowing on a small lake, aimlessly. From history, therefore, we can see how the choirs sang in circles, semicircles and in various other ways, taking up more or less informal and sometimes dynamic geometric designs. According to *Ehmann* the "choral line" was born with the operatic productions of the eighteenth century and continues in concert halls during the following century. In the theater halls produced later the choir is somehow forced onto the stage and to perform in more or less straight lines due to the roles associated with the characters. The size of the choirs can also influence the narrow spacing between the singers and the fact of making the formation more linear rather than circular. Since choral music is a hybrid of music and text, it finds more difficulty than instrumental music in finding autonomy in the aesthetic framework. Nowadays the use of choral risers can reinforce the idea of the chorus sound as a stand-alone object.

(16) *Daugherty* conducted an experiment with 20 choristers (10 males and 10 females) and 60 listeners (all with choral musical experience) to verify their preferences both regarding the spacing between the choristers (*closed*, *lateral* and *circumambient*) and the formations (*section*, *random blocks* and *synergistic* or the habitual training of the choristers). The choristers belonged to a university chamber complex of the Midwestern United States; everyone had taken singing lessons, so they had a well-trained and experienced choral voice. A cappella and Latin text homophonic music was chosen (according to the listeners a foreign text would have facilitated the concentration on the choral sound). Generally, the following results were found:

- The singers preferred a widespread spacing. There were fewer vocal tensions and therefore better vocal production;
- Listeners preferred circumambient spacing for female choristers, while, lateral spacing for males.

The spacing of the choir in this case is seen as a means of contributing both to the ease of vocal production and to a desirable choral sound.

Melius Christiansen supports the compatible positioning of the voices in the choral ensemble. According to *Daugherty,* this method of placement had a pedagogical benefit as it encouraged the sensitivity of the singers towards their individual contributions to the ensemble sound. Chorus directors use various methods and strategies for placing singers to produce a pleasant choral sound: height, rhythmic skills, vocal timbre, strong or weak singing. Nevertheless these criteria have not been empirically investigated with respect to acoustic contributions.

In the following figures show the spacing taken into consideration by the author: closed, lateral and circumambient.

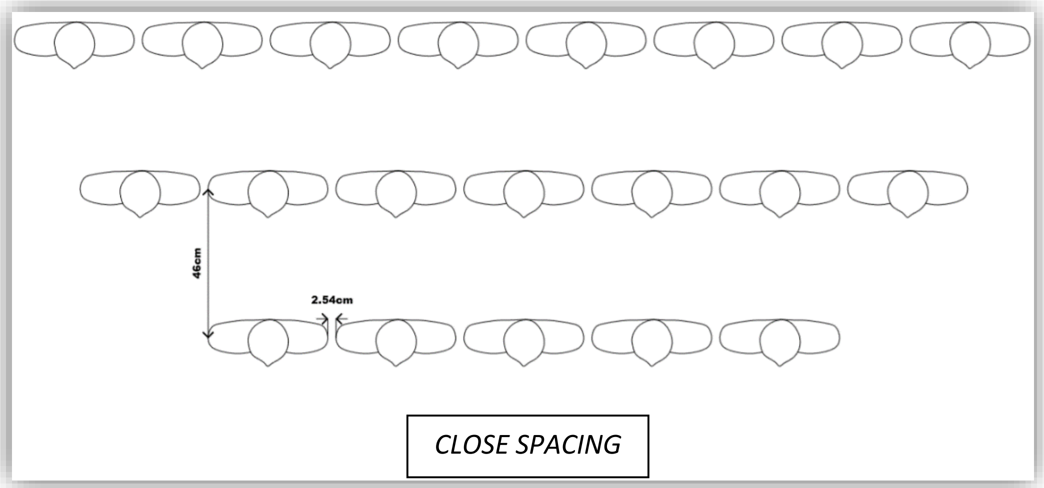


Figure 7 In the close spacing the singer's upper arm is nor more than 1 inch (2,45cm) from that of the neighbor

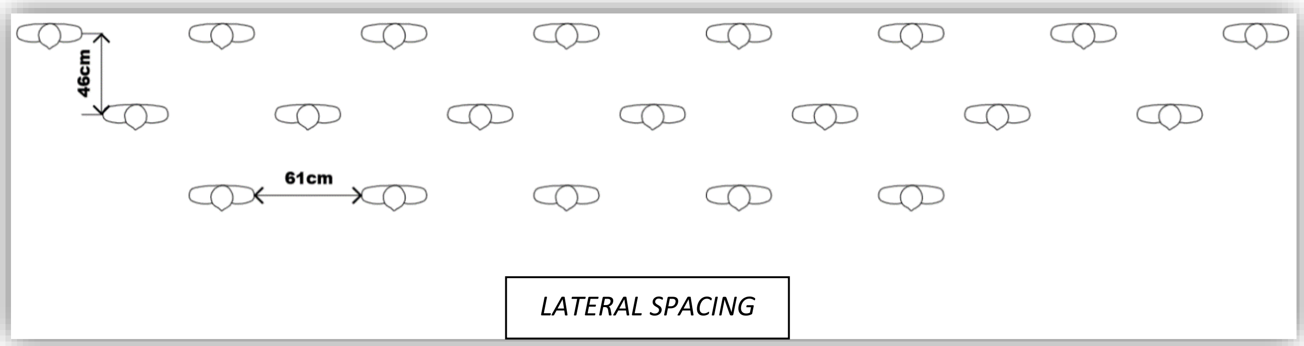


Figure 8 In lateral spacing the upper arm of the singer is 24 inches (61cm) from that of the neighbor

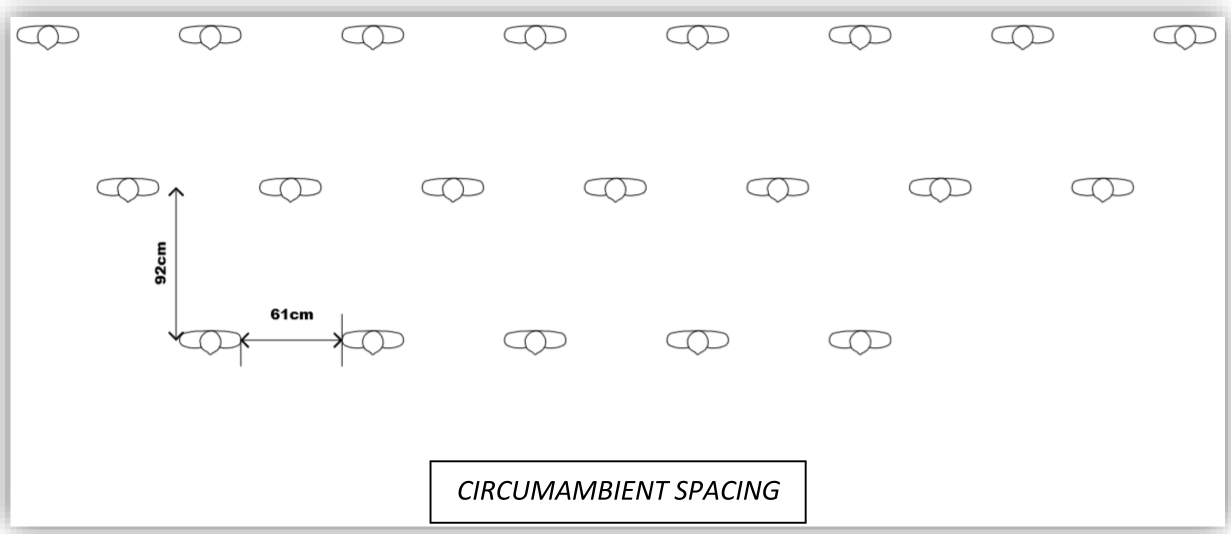


Figura 9 In the circumambient spacing the subjects are arranged as in the lateral one but between one row and the other there is a free row

Both the singers and the choir director agree that the spacing influences the choral sound and the choral technique. According to 75% of the choristers, circumambient spacing has a greater influence on the sound than on the lateral one. As for the formation, the singers preferred their usual formation, the synergictic one, over the random one. In the following table we can summarize the results.

	Spread spacing	**Close spacing**
Hear/Monitor your own voice	95% of choristers preferred spread spacing. Of these, 35% preferred lateral spacing while 60% circumambient spacing. The latter was preferred by all tenors and 75% of sopranos.	
Hear/Monitor of the best sounf of the choir	55% of the singers preferred the spread spacing. Equal preference between lateral and circumambient spacing.	45% of the singers preferred the close spacing.
Vocal tension		The singers felt more tension in the close spacing. In this case they tended to sing louder.
Synergic formation		95% of the singers preferred a close spacing as it is the one they usually use.
Random formation	*Best tone*: 85% of the singers preferred the spread spacing. Of these, 35% preferred lateral spacing, while 50% circumambient spacing. *Best choral sound*: 75% of the singers preferred the spread spacing. Of these, 35% preferred lateral spacing, while 40% circumambient spacing.	
Gender random formation	*Best tone*: Preference for circumambient spacing; *Best choral sound*: 50% of female choir singers preferred circumambient spacing, while 60% of men preferred lateral spacing.	
Choir director	Preference for diffuse spacing.	

Table 10 Summary of preferences concerning Spread and Close spacing

As far as the listeners are concerned, the following cinsiderations can be made: for all the performances (whole choir, only female ensemble, only male ensemble) they preferred a spread spacing. In particular, as regards the male ensemble, there was a greater preference for lateral spacing. Whit regard to formation, instead, there is a preference for the random one with respect to the synergy.

2.5 Directivity of choral singers

The factors that can influence the directivity of a source are as follows (17):

1. Source geometry;
2. Diffractive / reflective behavior of the sound source;

3. Behavior of surrounding obstacles.

In a choral situation, singers are usually placed side by side and on several rows; for this reason everyone can be a reflective or diffractive obstacle. *Harald Jers* conducted an experiment using an artificial singer (positioned at 180cm height) and fictitious head obstacles as a sound source.

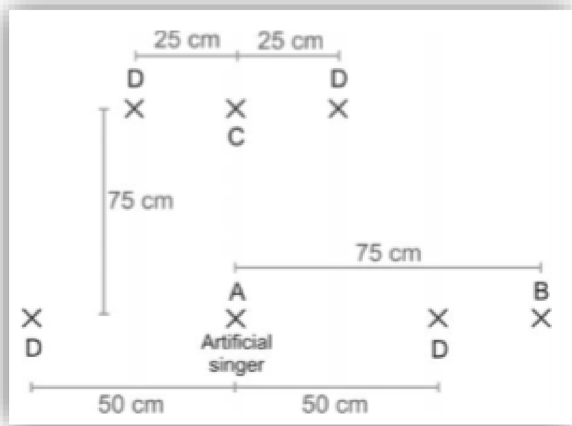


Figure 10 Positions for the study of directivity conducted by Jers

Position A: Artificial singer;

Positions B, C, D: Positions of nearby singers (fictitious trunks).

The results show differences compared to solo singers:

- *Lateral singer*: seems not to have much influence on the directivity of the singer;
- *Frontal singer*: it influences directivity especially for higher frequencies. For those greater than 800Hz there seems to be a shading effect in the frontal direction. We also note a decrease in the SPL in the main direction of the frontal radiation of about 20-25dB; on the back the SPL increases up to 10dB;
- *Surrounded singer*: with four surrounding singers there is a noticeable influence on directivity. Reflections towards adjacent singers increase the overall SPL by at least 5-10dB, even for low frequencies. The effects of shadows create a rather complex pattern of directivity around the singer. In the straight direction of an adjacent singer there is a reduced SPL; in the spaces between the surrounding singers, however, there is an increase in SPL. This is due to the reflection on the bodies of the surrounding singers. The use of risers can be very important precisely for this reason: the fact of standing on several rows not one behind the other but at different heights and / or positions is advantageous both visually and acoustically.

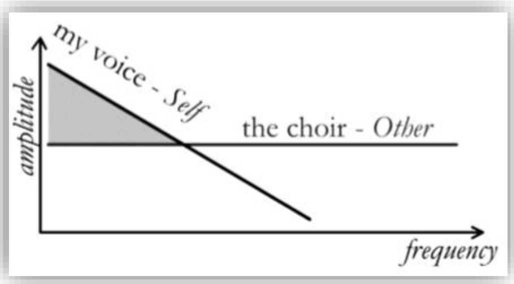
3. *"SELF TO OTHER RATIO"* PARAMETER, SOR

During a choral performance it is very important to be able to hear one's own voice and that of others in a balanced manner. If this doesn't happen there may be several problems concerninf, for example, rhythm and pronunciation (18). The parameter *SOR*, *Self to Other Ratio*, calculates the ratio between one's own voice and that of the others in dB.

3.1 *SELF* AND *OTHER* SOUND

The sound of our voice, called *Self*, reaches our ears through three separate paths:

a) **Sound transmitted from the air** it is the sound that comes out of the mouth and comes directly to our ears. Through this path we hear our voice more polarized towards low frequencies, therefore with less high, due to the dependence between directivity and frequency. High frequency sounds (high and hissing tones) tend to travel straight as they have a short wavelength. The lower frequencies that have a longer wavelength than the size of the head are able to spread around the cheeks and reach our ears directly.
b) **Bone sound** corresponds to the buzz of the vocal cords transmitted through the skeleton to the middle ears. Also in this path the high frequencies are lost. Ternstrom does not consider this sound in the calculation of the *"Self"* level, which is determined only by the sound transmitted from the air.



Our voice reaches our ears with an increase in bass and a reduction in treble; this guarantees that during a choral performance there is, more often than not, a low frequency part of *"Self"* which dominates over *"Other"* (18).

Howell has identified several types of vibrations determined by tissues and muscles (19):

1. Vibrations associated with the movements of the vocal cords that force the bones to vibrate;
2. Vibrations caused by the movement of air in the vocal cavities.

Tonndorf has divided the sound paths that transmit sound through bone conduction into three components:

1. *External component*: produced by the vibrations of the walls of the anterior channel that radiate the sound in the ear canal. According to Bekesy this component is attributed to the movements of the lower jaw. Allen, Fernandez and Dieroff instead affirm that the lower jaw only slightly influences this component, which is affected above all by the different transmission paths.
2. *Medium component*, includes the sound in the auditory system due to the ossicles and the eardrum. It is based on the inertia of the masses of the ossicles, which are stimulated

by the vibrations of the skull and, not being strictly fixed, can vibrate with a phase delay with respect to the vibrations of the skull and the cochlea.
3. *Inner ear*. The main idea is that stimulation takes place directly in the cochlea; it is the result of compressive deformations of the bone cochlea or fluid inertia.

Through various investigations it was found that the sound conducted by the bone and the sound conducted from tha air have the same order of magnitude as regards the volume.

Furthermore, according to the experiment conducted by *Bakesy*, the following results were found:

1. The perception of sound conducted by the bone has the greatest influence at around 1kHz;
2. Bone conduction is dominant in the range of frequencies between 700Hz and 1200Hz;
3. The sound conducted by the air prevails in the other frequency bands;
4. The sound carried by the bone is more important in the low frequency area.

c) **Reflected sound** corresponds to the reflection of one’s voice caused by acoustically relevant surfaces placed in the surroundingenvironement (the place where we find ourselves determines how we hear our voice) (19). The reflections are treated as external sound sources. According to Dunn and Farnsworth, the voice of a person can be modeled through a source placed at the opening of the mouth taking into consideration the following factors:
   1. Directivity of the sound source caused by the shadow effects of the head and body;
   2. Directional effect due to the size of the mouth opening.

The three routes described above are represented in the following image

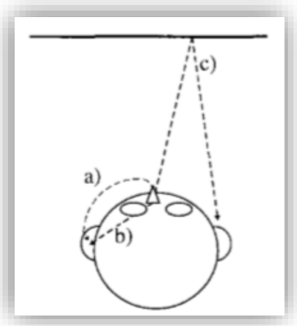


Figure 11 a) Direct sound; b) Sound conducted by the bone; c) Reflected sound

The sound of the other singers, named *Other*, reaches our ears through three paths (Ternstrom treats only the first two in his treatment) (18):

1. **Direct sound**: travels directly from the mouth of a chorister to our ears; is dominated by nearby singer. It weakens as the source-recever distance increases. The sound becomes weaker with increasing distance; referring to the *law of distance* with the doubling of the distance there is a decrease in the intensity of 6dB. For this reason, if the chorister are arranged with close spacing, the distance between them will be smaller so the sum of the direct sounds will be stronger. Therefore, i twill be more difficult to listen to one’s own voice.

By increasing the spacing decreases, instead, the sound of the other singers decreases with an increase in one's voice and therefore a higher value than the *SOR* (20).

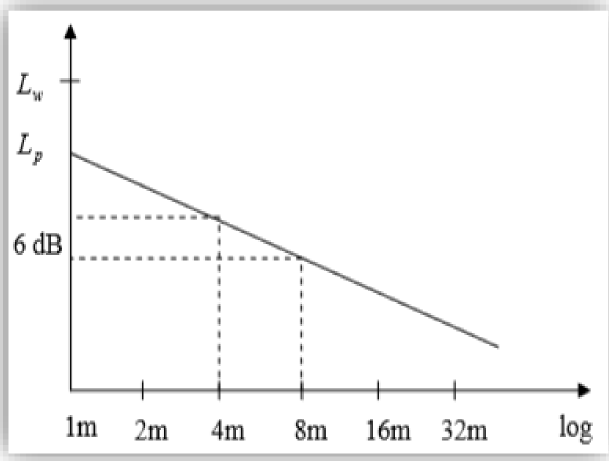


Figure 12 Doubling the source-receiver distance results a decrease of 6dB (21)

2. **Reverberated sound**: corresponds to the sound bouncing around the room. Each singer creates many mirror images that in turn act as sound sources. These are called secondary sources and generate a weaker and slightly delayed sound than the direct one. All these sounds help determine the *diffuse field*. In a reverberating room we speak of a strong diffuse field when the sound energy is kept longer. In a damp room, however, the sound energy is absorbed more quickly by the walls so the diffuse field is weaker; in this last case the choral mixture is less complete. In outdoor areas, there is no diffused field.
The scholar W.C. Sabine has defined the *reverberation time* as the time required for the sound level at a point in the room to decay by 60dB from the moment of turning off a sound source that emits a stationary signal.

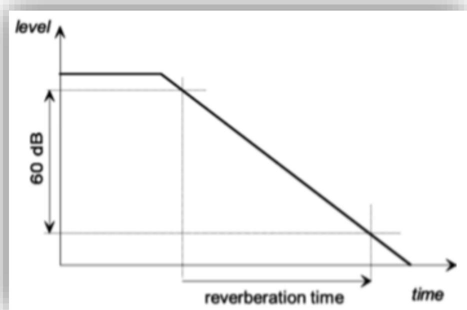


Figure 13 Reverberation Time (18)

$$T_{60} = 0.16\frac{V}{A}$$

Where:

V=Volume $[m^3]$;

A $=\sum a_i S_i = a_m S$= *Equivalent absorption area*

Based on the volume of the room an optimal value of the reverberation time can be determined ($T_{60,ott} \cong 0.1\sqrt[3]{V}$ music (21)).

With the *reverb ray* parameter we indicate the distance from a sound source in which the direct sound level is equal to the diffused field level that derives from the reverberated sound of the source. Our ear perceives the diffuse field to dominate beyond a triple distance from the reverberation ray.

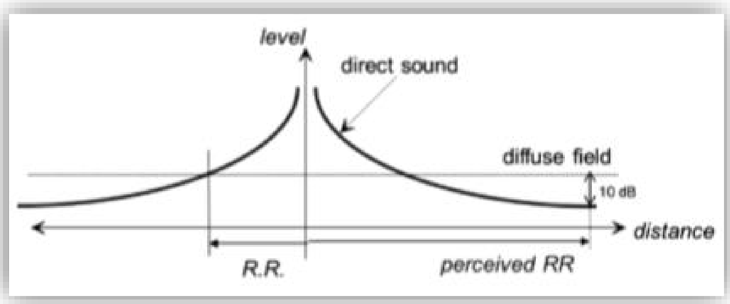


Figure 14 Reverb Ray

3. **First Reflections**.

The absorption of the room has a strong influence on the level of *"Other"* since most of the voices of the choir reach our ears like a diffuse sound.

Not hearing your own voice well can lead to problems related to pitch and vocal timbre, while not hearing the sound of other choir members can bring time- related problems. In the following table we can summarize the factors that allow us to increase the two sounds.

Increase factors for "Self"	***Increase factors for "Other"***
Personal reflectos	Room reverberation
Wide/mixed formation	Close/Sectional formation
Small choir	Big choir

Table 11 Increase factors for "Self" *and* "Other" *(18)*

3.2 DEFINITION AND MEASUREMENT

The *SOR* parameter determines the relationship between the *"Self"* level and the *"Other"* level. It corresponds to the level difference, expressed in dB, between the sound pressure level (*SPL*) of the *Self* and that of *Other*.

$$SOR = SPL_{Self} - SPL_{Other}[dB]$$

A positive value of this parameter determines how much we hear our voice more than that of others.

This parameter is influenced by two factors:

- *Choral formation*: the spacing between the singers affects the direct sound intensity of "*Other*". This component decreases with distance causing an increase in SOR. In fact, as the distance between the singers increases, we hear our voice more than that of others;
- *Room acoustics:* The equivalent absorption area influences the intensity of the diffuse field. Increasing the reverberation reduces the *SOR* (we hear less our voice).

The problems that may occur in cases of non-optimal SOR can be summarized in the following table (22).

Condition	Masking	Problem
Reverberating rooms; Narrow formations.	Own voice "Self"	Pitch; Voice timbre.
External environment; Scattered formations.	Rest of the choir "Other"	Time

Table 12 Problems caused by a non-optimal SOR

(23) For the evaluation of the SOR we must consider the sound field as experienced by the singer or something similar to it. For this reason, Ternstrom in his experiments to calculate the parameter, made the subjects wear a pair of lightweight binaural microphones. These are similar to a stethoscope, they allow to have a transducer in every external ear, near the entrance of the auditory canal.

Figure 15 Example of how binaural microphones were worn in the experiment conducted by Ternstrom

Considering the signal of our voice, *"Self"*, which represents the *Feedback*, arrives identical and in phase in all the frequencies in the two ears. This signal in the treatment corresponds to the sum of all the sounds conducted by the air without counting the reflections of the room and the sound conducted by the bone. With the term *Reference* we indicate instead the signal *"Other"*, therefore the sound of the rest of the choir. It corresponds to the total power that arrives in the left ear (*L*) and in phase opposition in the right one (*R*). This signal is different in the two channels as it corresponds to the sum of many symmetrical and incoherent sources.

Considering the signal that reaches the left ear *L* and the one that reaches the right ear *R*, I will have:

$$L = Self_L + Other_L,\ R = Self_R + Other_R$$

Where:

$$Self_L = Self_R$$

$$Other_L \neq Other_R$$

The *"Self"* signal can be approximated by creating the sum signal *M*

$$M = L + R$$

The signal *"Self"* in fact being equal in *L* and in *R* will be double so it determines an increase in gain of + 6dB; the *"Other"* signal, on the other hand, not being consistent leads to an increase of only +3dB. The latter can be approximated with the difference signal *S*

$$S = L - R$$

In this case the *"Self"* signal will be canceled while the *"Other"* signal will result in an increase of +3dB compared to its *SPL* in *L* or *R*.

L, R, M and *S* are all sound pressures. *Feedback* and *Reference* are sums of different sound pressures and are measured in two points for the stereo and stored on the two channels *L* and *R* (which carry a mix of two stereo signals).

$$M = L + R = Self_L + Self_R + Other_L + Other_R = \underbrace{2 \times Self}_{+6\text{dB}} + \underbrace{Other_L + Other_R}_{+3\text{dB}}$$

$$S = L - R = \cancel{Self_L} - \cancel{Self_R} + \underbrace{Other_L - Other_R}_{+3\text{dB}}$$

$$SPL_{Self} = SPL_M - 6dB$$

$$SPL_{Other} = SPL_S - 3dB$$

$$\boldsymbol{SOR} = SPL_{Self} - SPL_{Other}[dB] = SPL_M - 6dB - (SPL_S - 3dB) = SPL_M - 6dB - SPL_S + 3dB$$

$$= \boldsymbol{SPL_M - SPL_S - 3dB}$$

$$SPL_M - SPL_S = SOR + 3dB$$

This method is true the following considerations a e [b or (c and d)] are true:

a) $Self_L$ and $Self_R$ are so dissimilar that in S they are canceled (in this case Self must be much weaker than Other);
b) *"Self"* is stronger than *"Other"*;
c) *"Self"* should not be weaker than -3dB compared to *"Other"*;
d) $Other_L$ and $Other_R$ are so different in *S* that the salient properties of the signal are preserved.

Summarizing the nomenclature used to measure this parameter we have the following definitions

- *Reference*: indicates the sound of the rest of the choir;
- *Feedback*: indicate the total sound of your own voice;
- *L*: Aerial sound signal acquired by the singer's left ear;
- *R*: Aerial sound signal acquired from the singer's right ear;
- *M*: Sum of *L* and *R* (*L*+*R*);
- *S*: Difference of *L* and *R* (*L*-*R*);
- *Self*: Part of air feedback as represented in *L* and *R*;
- *Other*: Reference as represented in *L* and in *R*.

In the following table we can summarize the advantages and disadvantages of using this method (22)

Advantages	Disadvantages
It is not affected by the subject's position	Discrimination *"Self"*/*"Other"* depends on frequency
It is not affected by the orientation of the head	The left / right correlation of *"Other"* should be considered
It is not affected by the acoustic details of the room	

(23) The purpose of good reception corresponds to the adaptive control of the fundamental frequency, power and vocal spectrum. The masking exercited by other choir singers is very powerful because the masking signals are very similar and in many cases correlated with the target signal. In fact, many times the singers cannot distinguish their own voice.

3.3 CALCULATION OF THE SOR PARAMETER

Knowing the following parameters it is possible to make a forecast of the average SOR (23);

1. Room absorption;
2. Choir topology;
3. Assumption that all singers emit the same acoustic power.

As explained by Ternstrom in the paper *"Hearing Myself with Others: Sound levels in choral performance measured with separation of one's own voice from rest of the choir"*, the *Self-To-Other-Ratio* can be calculated as follows.

1. Find the **area of equivalent absorption** and the **average absorption of the room**
   From Sabine's formula
   $$T = 0.161\frac{V}{A}\,[\mathrm{s}]$$
   $$A = 0.161\frac{V}{T}\,[m^2]$$
   Where:
   T = Reverberation time [s];
   A = Absorption area $[m^2]$;
   V = Volume $[m^3]$.
   Find the absorption coefficient $a_m$through the the Eyring formula (21)
   $$T_{60} = \frac{0.161V}{S[-\ln(1-a_m)]}$$
   $$A = S[-ln(1-a_m)]$$
   From which revenue
   $$a_m = 1 - e^{-\frac{A}{S}}$$
   Where:
   S = Total Surface Area $[m^2]$.
2. Considering the SPL of the entire choir, I calculate the **intensity at one point in the diffused field**

$$SPL = 20log\frac{P}{P_0} = 10log\frac{I}{I_0}$$

Where:

SPL is the *Sound Pressure Level* calculated with the sound level meter in the conductor's position during the measurements (while the whole choir sings).

$I_0 = 10^{-12}\left[\frac{W}{m^2}\right]$

$$I = 10^{\frac{SPL}{10}} \times 10^{-12}\left[\frac{W}{m^2}\right]$$

3. From intensity I calculate the **average power per singer**

$$W_{tot} = \frac{IA}{4}[W]$$

Where:

W_{tot} is the power of the whole choir [W];

I is the intensity calculated in the previous point $\left[\frac{W}{m^2}\right]$;

A is the asbsorption area $[m^2]$.

Dividing it by the total number of singers (N) I get the contribution of the individual

$$W_i = \frac{W_{tot}}{N}\ [W]$$

4. Calculate the **SIL** (*Sound Intensity Level*) **of "Other"** from the average power of the singer. Considering the level of sound intensity within the choir (24)

$$I = \frac{GW_i}{4\pi {d_e}^2} + \frac{4W_i(1-\alpha)}{A}\left[\frac{W}{m^2}\right]$$

Where:

G = Directivity factor;

W_i = Power emitted from the source [W];

d_e= distance between the singers;

$A = -Sln(1-\alpha)$ = Room equivalent absorption area $[m^2]$;

α = average room absorption coefficient.

We can consider the first term belonging to the direct sound and the second term to the reverberated sound.

Assuming to have a chorus composed of *N* members, with the same irradiation power, we can express the total intensity at a given point in the room as

$$I = \frac{W_{tot}}{4\pi}\sum_{i=1}^{N}\frac{G_i}{d_i^2} + \frac{4NW_i(1-\alpha)}{A}$$

Where:

d_i=distance of the i-th singer;

G_i=Directivity factor of the i-th singer considered from the listener's position.

The intensity of the direct sound of all the *N* singers can be approximated by the intensity of a sound directed by an equivalent number of n_e singers, placed at the same equivalent distance d_e. Assuming that *G* is on average 1 for an arbitrary position of the listener, the term of the dirct sound becomes

$$\frac{W_i n_e}{4\pi d_e^2}$$

For a listener $n_e = N$ while d_e corresponds to the distance of the choir. If the singers are close enough and in front of the audience one should also include *G* with a value of about 2 in the numerator. For a position inside the choir, the direct sound is dominated by the neighbors. If the chorus is arranged in two lines, many singers will consequently have five close to an equivalent distance of d_e which can be calculated as the inverse of the square root of the inverse of the neighbors that is

$$d_e = \frac{1}{\sqrt{\frac{1}{5}\sum_{i=1}^{s}\frac{1}{d_i^2}}}$$

Since the singers are facing in various directions with respect to the point of interest, it is possible to approximate G to 1. Based on the size of the choir the contribution of the direct sound intensity of the remaining singers will be equivalent to one or two next neighbors. So the level of sound intensity that reaches a listener inside the choir can be expressed as

$$I_{Other} = \frac{W_i n_e}{4\pi d_e^2} + \frac{4NW_i(1-\alpha)}{A}\left[\frac{W}{m^2}\right]$$

$$SIL_{Other} = 10\log\left(\frac{I_{Other}}{I_0}\right)\ [dB]$$

Where:

$n_e = number\ of\ neighbors;$
$d_e = distance\ between\ neighbors.$

5. Calculate the **SIL di *"Self"*** from the average power of each singer (*Sound Intensity Level*). Considering the opening of the mouth as a source of points free at 15cm (*r*) from each ear

$$I_{Self} = \frac{W_i}{4\pi r^2}\left[\frac{W}{m^2}\right]$$

$$SIL_{Self} = 10\log\left(\frac{I_{Self}}{I_0}\right)[dB]$$

This value can be increased by the presence of the head, but the directivity would decrease it.

6. Calculate the **SOR**

$$SOR = SIL_{Self} - SIL_{Other}\ [dB]$$

3.4 Optimal values obtained from the experiments

3.4.1 SOR favorite

Ternstrom in 1999 studied the SOR parameter preferred by the singers (22). The subjects that took part in the experiment are in total 23: 6 Basses, 6 Tenors, 6 Altos and 5 Sopranos (females). Everyone had at least 5 years of choral singing experience.

For the experiment the subject was positioned 1.5 meters away from the wall on which four equidistant speakers were mounted from the participant's head. A microphone was placed next to him whose sound level was used to control the volume of the chorus synthesized in real time coming from the speakers (in counter-phase so as not to have apparent sources in the center of the stereo image). In this way the *SPL* (sound pressure level) of the subject controlled that of the choir. The synthesized chorus was reproduced by the speakers only when the subject sang. The SOR, to the subject's ears, was independent of his *SPL* (each change in the subject's *SPL* resulted in a change in that of the choir): by approaching the microphone the relative level of the choir was raised, therefore there was a decrease in the *SOR*; moving away from the microphone instead the level of the choir was lowered with a consequent increase in *SOR*. The objective of the subject was to search for the optimal distance from the microphone in which the balance between his own voice and that of the others was perceived. Once the position was found it was necessary to press a button and continue singing for at least 5 seconds. Finally, during these 5 seconds, the *SOR* was calculated thanks to a pair of binaural microphones worn by the subject.

To carry out the experiment the following three factors were taken into consideration:

1. Better to carry out the experiment in a reverberating room than the anechoic one (not appreciated by the singers);
2. The stimuli must be presented through loudspeakers and not headphones since, the latter, interrupt the normal auditory feedback and fix the positioning of the sound field of the estimate relative to the subject's head;
3. The microphone signal in front of the subject is not used to calculate the SOR but only to acquire the subject's SPL and then adjust the speaker level.

The experiment was carried out taking into consideration two contexts: unison and fourth part of the agreement; moreover two levels of the fundamental F_0 and three vowels [u:], [a:], [ɛ:] have been chosen. Only stationary sounds were used for the following reasons:

- Focus the experiment only on sound levels (the acoustics of the ensemble are not considered);
- It avoids the complication of the accidental variations of the *SOR* concomitant with changes induced by the text in the change of the vowels and of the vocal effort (this happens when *"Self"* and *"Other"* are not perfectly in sync);
- The *SOR* in stationary conditions can be considered closely related to the average SOR in music;
- Eliminates the need for subjects to learn to sing a particular piece of music;
- Allows subjects to focus on balancing their voice level and to a lesser extent on the timbre.

The preferred average total *SOR* was + 6.1dB, with an average intrasubjective standard deviation of 3.1dB. These preferences were also found in live choirs.

Although we expected a major *SOR* in the unison context, analyzing the variance there were no differences in this respect (unison/chord). The average level of the *"Self"* in the context of the chord was 7.6dB lower than that found in the context of the unison. In the first case the sound of the choir was softer so this induced the subjects to sing in a softer shade.

Generally, two characteristics can be found:

1. The effect of the F_0level was significant only for bass and tenors; for both the preferred SOR increased with the increase of F_0;
2. For sopranos, no factor had a significant effect on the preferred SOR; this could be due to the fact that sopranos vary less with vowels, especially at high F_0, where all vowels tend to approach [a:].

The preferences regarding the SOR differ from the different sections. There is a general tendency for higher SOR values for sopranos and lower for bass.

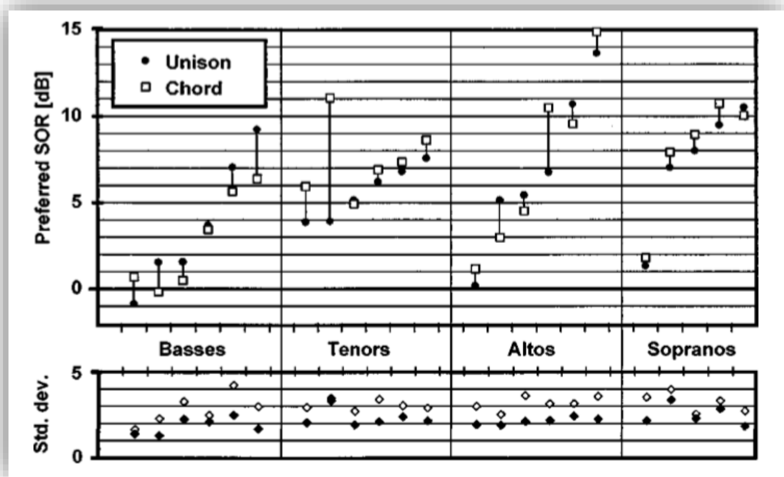


Figure 16 SOR preferred in the two cases unison and chord for the various sections. Below are the relative standard deviations.

In normal choir music, with constantly changing levels, tones and vowels, the SOR changes rapidly. The agreements supported are very important when considering the SOR, in fact the auditory feedback is fundamental to correct and pre-pack the intonation.

The great intrasubjective variation in SOR preferences can be attributed to the habitual position of the singers in the choir. Subjects located at the end of the choir prefer a higher SOR, whereas those in the middle of the choir prefer a negative SOR. This implies that the SOR preference is partly acquired and not determined by only acoustic factors.

Coleman in 1994 reiterates that singers in the same choir can greatly vary the output power of their voice; for this reason the preferences of the SOR parameter can vary considerably. Singers with soft voices will have a greater advantage if positioned at the ends of the choir. The greater the number of rows in which the choir is, the greater the influence of the position within the choir.

3.4.2 Opera Choir

In 2005, *Ternstrom, Cabrera* and *Davis* carried out an experiment with four members of the Australian Opera choir during the penultimate dress rehearsal on stage at the Opera Theater of the Sydney Opera House (20). Each of the four choristers was part of a vocal category (soprano, mezzo-soprano, tenor, baritone) and on average they were between 38 and 56 years old. During the test, to measure the parameter, they had to wear a pair of binaural wireless microphones placed in front of the ears about 14cm along the circumference from the center of the mouth (not ideal positioning as the membranes were not positioned inside the pavilions). Only the parts in which the choir was actually singing were considered, for a total of 200s for the female voices and 800s for the male ones.

Characteristics of the parameter:

- The SOR of the opera choir depends mainly on the formation (it can be near or diffused and vary frequently); an artist of the opera choir can listen to his own voice well and little to the others and the orchestra.
- Due to the various changes in the decorations during the performances, the SOR is very variable.

The method used to calculate the *SOR* is the one described above in the "Definition and measurement" paragraph with the use of a pair of binaural microphones. For this reason, the microphones were initially calibrated, to avoid clipping, and the two left right channels were paired to allow the cancellation of the *"Self"* signal. To obtain the correspondence of the channel gains, the equivalent level was calculated, L_{eq} (which indicates the average energy level of the signal), on each file.

The acoustics of the stage are influenced by theatrical furnishing, which has been changed a few times during the recordings but each time with poor results (a few reflective side walls). In this case the parameters considered are the *support for the initial phase* (*ST1*) and the *support for the late phase* (*ST2*).

ST1 corresponds to the dB ratio of the energy initially reflected within the 20-100ms period relative to the direct sound taken in the first 10ms of the impulse response. It refers to the ease of listening to other members of an ensemble). *ST2*, on the other hand, corresponds to the ratio of the reflected energy after the first 100ms with respect to the direct sound. Both must be measured at a distance of 1m from the acoustic center of an omnidirectional sound source.

To measure the two *ST* a dodecahedral speaker and a microphone was used at a height of 1.5m. The measurements were made in 15 positions and for each one four measurements were taken, based on the directions (north, south, east, west), from which the average was taken.

Average SOR (for a duration of 2-20s per extract):

- Soprano: +15dB;
- Mezzosoprano and tenor: +10dB;
- Baritone: +14dB.

These results may be underestimated due to mismatches of the left and right channels.

Regarding the results concerning Stage Support:

- Average of *ST1* under the proscenium arch 2m from the front edge of the stage: -16,2dB.
- Values of *ST2*: -20dB (Particular as it is less than *ST1*)

Chamber music rooms tend to have more support in the initial phase. The studies of Gade 1989 and Jeon and Barron 2005 show that the support of the stage can be modified in a given auditorium by changing the position of the reflective surfaces above and around the stadium. Measurements indicate that a small reverberation would be audible to a singer due to its high sound absorption. The support for the initial phase increases towards the back of the stage, while the support for the late phase decreases.

It can be seen that with a strong diffuse field, there will be a low SOR value and depending on the total number of singers, instead, with a weak diffuse field, the SOR will depend on the number of neighbors that are closer to the reverberation ray. On the operatic stage, the greater absorption of the room and the spacing between the often wider singers have been compensated by the more powerful voices of the choir artists with vocal skills that would be consistent with the higher SOR values. In chamber choirs the individual SOR averages tended to be larger for sopranos and lower for basses, with highs and tenors in between.

For the maintenance of time, one often has to rely on eye contact with the handler or on stationary estimation since the opera choir artists can only hear the orchestra incidentally and the soloists and the rest of the ensemble often sound distant.

3.4.3 Chamber choir

The experiment was attended by 20 singers belonging to a well-known mixed chamber choir (soprano, alto, tenor and bass); they sang, arranged in a single semicircular row, a homophonic memory chorus, normally used as a processional hymn (it does not have very high and very low notes).

The subjects were asked to sing the extract with the choir (*"Tutti Condition"*), sing some lines of the piece by themselves (*"Solo Condition"*) and in some cases remain silent while the others sang (*"Silence Condition"*). The second condition served to eliminate the small asymmetries in the position of the microphones and the small differences between the subjects that tended to produce small variations of the gain between the left and right channel.

The mean of the SOR calculated between all 12 singers was + 3.85dB (variations between +1.5 and + 7.3dB). The standard deviations had an average amplitude of 3.46 dB. When the subjects sang alone a SOR of +11.6 and + 18.7dB was calculated. The diffuse field of reflections of one's voice in the room is at least 10dB weaker than the sound of other choristers. This implies that the reflections of the singer's voice are masked by the choir. It was found that when the singers sang alone they sang more sweetly (average drop of 1.7dB). It is also noted that the sopranos sang louder than the others; this explains why their SOR is greater than the others. The *"Other"* SPL has an average of 88.3dB, with a standard deviation of 1.5dB.

From the acoustic point of view the room in which the experiment was performed was particularly dry or absorbent and the choir was quite small. Little of the power of the *Reference* originated from the singer or his symmetry plan. This resulted in a sound field in which the *Left* and *Right* signals were slightly in the opposite phase. There is the possibility that in a choir with multiple rows and in rooms with more reverberation, the relationships between the two signals are smaller and the SOR measurement is less informative. The *Left* and *Right* signals, although not coherent, must be statistically similar in amplitude both for the *Feedback* and for the *Reference*. The physical sound pressure level is not the same as the perceived volume. There is the possibility that bone conduction increases the observed SORs.

4. ACOUSTIC SHELLS

(25) A good listening experience can be subjective and complex, and there are other factors that cannot be controlled by acoustic design.

The propagation of sound in the open can be described through a free field acoustic model, in which the contribution to the total sound levels perceived comes only from the direct sound. This condition defines a non-uniform acoustic field. From the point of view of the public and of the musicians, the quality of this system depends both on the subject perceptions and on objective parameters.

Playing outdoors can lead to various problems for both musicians and the public (25) (26)

Musicians	Musical Perception	Acoustic Parameter
Problems in feeling with each other due to the lack of reflective surfaces. Without feedback the musician is not aware of what kind of sound reaches the ear of the listener and other musicians.	Ensemble	Stage Support
Due to the absence of reverberation there is an anticipated decay of the sound for chamber music. Musicians used to playing in reverberating rooms perceive an arid space.	Subjective reverberation	Early Decay Time

Table 13 Problems encountered by musicians during outdoor performances

Audience	Musical Perception	Acoustic Parameter
Due to the distance between the sound source and the public, there is a low sound level. The perception of musical dynamics is compromised.	No music	SPL (*Sound Pressure Level*)
Not uniform sound field. Irregular perception of the human ear of tones at different frequencies requires a carefully balanced selection of the reflected sound spectrum. Outdoors we have an unbalanced experience as there are no reflections.	Spatialization	Interaural Cross-Correlation

Table 14 Problems encountered by audience during outdoor performances

According to acoustics expert Beranek good acoustics is defined by the following elements: composition, conductor, orchestra, room (*"Concert Hall and Opera Houses"*).

Usually, active sound systems are used to solve the problems of playing outdoors. These, however, could produce some distortions in the processing of the audio signal: alteration of the frequency spectrum, difficulty in identifying the true sound source, change in the nature of the sound (in particular timbre and color). For these reasons we tend to use passive acoustic systems. Since a reverberant field propagation state cannot be reached outdoors, the corrective strategy consists in designing a system of reflective and diffusive devices in the form of a reverberant acoustic chamber.

4.1 USES OF THE ACOUSTIC SHELLS

The acoustic shells for outdoor concerts are a specific subclass of passive acoustic systems designed to amplify and evenly distribute the sound on an area of the public in external conditions (27).

According to *Jaffe* most of the external structures that aim to improve the sound follow one of the following two models (28):

1. Shells that surround the artists on stage, capture the sound energy and project it onto the audience seated in an amphitheater or on a lawn. This type of acoustic shell improves the acoustic conditions for both artists and the public; in the first case offering early reflections from multiple directions so that musicians can listen to themselves and others, in the second case amplifying and enlarging the source image.
2. Shed open on the back and sides, covered by a roof that protects members of the public from the elements and allows the glare to accumulate. They often include a stage fence and a raised reflector to support musicians and increase the level of clarity and early sound energy for audience members.

(29) The shells can be represented by complex curved surfaces that manage to evenly distribute the sound energy within a space; from the structural point of view they are able to transport structural loads very efficiently.

4.2 ACOUSTIC SHELLS IN LITERATURE

4.2.1 Transportable acoustic shells

4.2.1.1 Tiara

Figure 17 The Tippet Rise Tiara costructed in July

(30) In 2014, the Montana Tippet Rise Art Center commissioned Arup Acoustic to design an acoustic shell called "Tiara". This casing was used to host outdoor chamber music concerts for an audience of 50-60 people. The shell had to have the following characteristics:

- Temporary;
- Removible;
- Transportable.

The structure as well as recreating the acoustic intimacy of a small room had to allow the public to enjoy the panorama offered by the natural environment: the Tiara was located in an art center distributed on 11000 acres of ranch in the south of central Montana. In this regard, the concept of "room without walls" has been developed: for the visual objective, starting from a simple box, the surfaces have been cut, this has allowed to open the view to the surrounding valleys and mountains; to recreate the acoustic intimacy instead, we tried to optimize the remaining angles to provide an enveloping matrix of reflections to the artists and the public.

The acoustic objectives of the Tiara are to have a certain degree of amplification, magnification of the source and support of the stage but with a less frontal and more enveloping sound mark as well as a unified acoustic environment for artists and spectators to share. The baroque *Schloss Schwetzingen Rokokotheater theater,* whose acoustics are intimate and enveloping despite the short reverberation time and the *Esterhazy Palace Music Hall*, have been taken as reference points.

Figure 18 Schloss Schwetzingen Rokokotheater theater (45)

Figura 19 Music hall Esterhazy Palace (46)

Based on the 3D acoustic responses recorded by Bassuet we note that the room owes its surrounding acoustic qualities to the strong early reflections under the proscenium, the side walls, the ceiling and the curved balconies that compensate for the lack of reverberating energy. Since the reflections come from multiple directions and in rapid succession after the direct sound, they do not give rise to a displacement of the image but merge with the direct sound giving the listeners the impression that the voice of the opera singer fills the whole space. The uniform spatial distribution of sound energy is largely due to a series of reflections coming from the upper front and rear corners of the room.

The basic form referred to is that of a fan-shaped room of the following dimensions:

1. Width: 6,7m (front) and 9,8m (rear);
2. Depth: 7,6m;
3. Height: 1,5m.

From this basic form, half of each surface has been removed to keep only the corners, which reflect the sound of the artists and the public in all directions to create an enveloping and unifying sound environment. The goal is to optimize the angles to return more energy to the listeners, supporting the psychoacoustic impression of being in a room despite the lack of reverberation.

The effectiveness of each corner was evaluated through the geometric analysis performed with the ISM method (image source method). The upper corners covered a substantial part of the audience while the reflections of the lower vertical corners covered only a narrow band of audience members; just for this reason these last ones have been removed, leaving, therefore, only the surfaces above the heads of the musicians and the public. Considering a central listening position, according to the ISM analysis, there is a wide diffusion of incidence angles with second and third order reflections coming from the front, back and side.

The ISM analysis was then combined with the use of the *Galapagos* plugin to maximize the quantity and directional diffusion of the reflections reaching the musicians and the audience.

The result of the optimization has generated a downward angled ceiling compared to the public, a product of the reverse reflection path (from ceiling to side wall). The final geometry reports an average of 5,7s and reflections of the third order to each receiver (a reflection from the front, one from the left side and one from the right side).

From the acoustic point of view the reflected energy coming from the top was balanced and well integrated with the direct sound to create the enlargement of the dimensions of the source. Moving the stage closer to the public, from the point of view of the listeners, the balance has improved, from the point of view of the musicians, instead, a clear improvement was noticed in being able to listen to oneself and others.

To expand the Tiara in order to accommodate 80 members of the public, a fold was added to the arms of the structure and was re-optimized following the previous lines of optimization.

This structure manages to increase the commitment between performers and listeners, but, at the same time, invites us to contemplate the relationship between music and the natural environment; these relationships change based on its position within the Tippet Rise.

4.2.1.2 Soundforms

(31) The goal of Soundforms is to design a portable acoustic shell for orchestra that optimizes the projection of sound towards the audience area and the reflection of the sound on the stage to support the performers.

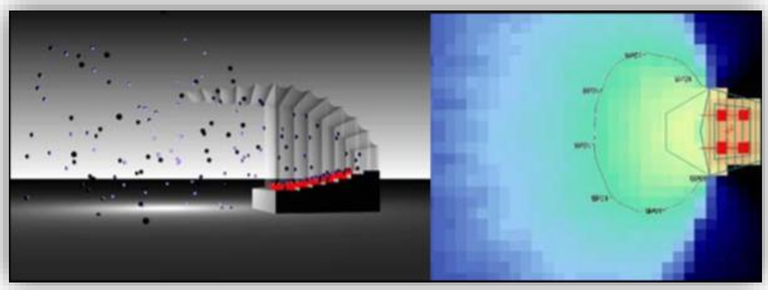
Figure 20 Soundform Acoustic Shell (47)

(32) *Mark Stephenson* presented the initial brief thinking about the design of the *Sydney Opera House* or the *Hollywood Bowl* in terms of visual and acoustic impact and the immediacy of the audience's reach.

Figure 21 Sydney Opera House (52)

Soundforms puts the accent on a wide dynamic range and a better definition and musical detail. Acoustic design takes place from the inside outwards, stimulating the sound directly towards the audience. The acoustic reflectors on the fixed truss and on the vertical side wing trellises create an internal surface that provides an acoustic dynamic on the stage, increasing the ensemble level between the different sections of a band or orchestra, allowing the artists to feel each other and provide more echoes. Musicians are able to listen to each other more clearly, ensuring higher performance standards. In the case of amplified concerts all the acoustic reflector panels can be removed.

The traditional orchestra shells used in internal situations such as theaters or churches are based on the sound reflection caused by the surfaces of the building; this helps improve the sound level for the audience. Outdoors, these reflections from the environment are missing, so for this reason, to increase the sound level for the public, a “peak” was designed which has the task of projecting the sound beyond the conductor, reflecting it towards the listeners.



Based on the technical specifications, Soundform has been designed in three dimensions with the same shape and design. The smaller one was designed mainly for acoustic concerts (for example string quartet, up to a maximum of 15 musicians) to be placed in spaces such as courtyards, squares, country houses etc. The average size, on the other hand, can accommodate up to 60 musicians for an audience of 500-2000 people (whether using high-tech audio systems or not) and is to be placed in large gardens, squares, exhibition centers. The larger one, on the other hand, is ideal for international festivals, parks, large public outdoor arenas, exhibition centers etc. as it can accommodate up to 100 musicians for an audience of 20000-40000 people (in this case with the help of high- tech).

(33) *Inflatable skin* The outer skin is composed of eight inflatable, waterproof, white polyamide cushions coated in PVC. The membrane being inflated to variable depths allows different tensile loads on the structure and guarantees a slightly curved and smooth exterior.

(33) *Timber acoustic panels* provide excellent acoustics similar to a concert hall and project sound onto the audience. Dimensions: 18mm, with a density of 500kg/m2. The panels are curved to reduce specular reflections and are angled to remove focus. They are suspended above the orchestra by a system of secondary pylons.

(31) Initially a profile was developed that extends the shell over the stage to increase the coverage of the sound at a further distance from the shell. The inner face has been paneled to create spot reflections to support the stage. The internal facets of the acoustic shell have been parameterized and through the optimization algorithms the dimensions and orientation of each facet have been refined to satisfy the acoustic objectives and the manufacturing and construction criteria. The objectives for optimization are the following:

1. SPL in the public area;
2. Parameter of the ST1 support on stage;
3. Physical release between the panels and the external surface of the structure;
4. Minimum space for the integration of stage lighting.

4.2.1.3 SuonoVivo

(34) SuonoVivo is a company that designs, builds and installs special acoustic rooms for orchestra and modular acoustic systems to overcome acoustic deficiencies in listening to classical music in opera houses.

Outdoor structures are constructed of transparent Lexan polycarbonate and PVC. The advantages of this structure are the following:

1. They actually play by amplifying the sound volume and enhancing the definition of acoustics;
2. They protect the orchestra from possible inclement weather by slowing down the dispersion of the sound mass produced and directing it incisively towards the public; moreover, they favor the sound comfort among musicians;
3. They have a wonderful aesthetic function: being transparent, they do not hide the surrounding landscape but tend to enhance it and embellish it.

The structures are modular and flexible, the dimensions are agile and compact.

4.2.2 Hollywood Bowl Shell

Figure 22 Hollywood Bowl with fiberglass spheres (48)

(35) The Hollywood Bowl is an Amphitheater located in the Hollywood Hills neighborhood of Los Angeles. It is known for its shell consisting of a set of concentric arches. Its "bowl" shape recalls that of the concave hill where the amphitheater is located. (36) Since 1922 it has been the main destination for live music in Southern California.

(35) Initially it was used as a community space; the first events were used to finance the construction of new elements of the structure (stage, seats, background of the proscenium).

The original shell, from 1926, was designed by the Allied Architects group and since it was not appreciated either from the acoustic or the visual point of view, it was redesigned by Lloyd Wright in 1927. It was built with a pyramid shape and a design reminiscent of architecture of south-western India. The shell with the best acoustics in the history of the Bowl was reputed, however, since from the visual point of view it was not reputed to the height, it was demolished. The shell designed the following year consisted of a concentric ring shape and covered an arc of 120 degrees; it was designed to be easily disassembled. In 1929 the Allied Architects had to reconstruct the shell because it was ruined by water. Although the acoustics were not the best, it was considered decent. Over time, even this deteriorated, so an inner shell was built, made up of large cardboard tubes that in the 1980s were replaced by fiberglass spheres. This contributed to worsen the acoustics: to perform and reach the entire audience, amplification had to be used. The appearance changed in the coming years for purely visual purposes: a large external arc was added. In 2003 the shell was replaced with a larger one that allowed for better acoustics. Despite the opposition of the conservatives it was not demolished and a clear improvement of the sound was noticed. The sound amplification system consists of a line-array configuration of several speakers hanging vertically in a curved way. Through the processing of avant-garde audio the audience in the rear sections can hear the same audio at the same level as the front sections. The shell of 2004 incorporates the important front arch of the 1926 calotte, the wide profile of the 1928 cap and the general lines of the 1929 shell.

(26) Hollywood Bowl Shell: the acoustic reflector has approximately the same area as the orchestra risers and is located at about 9.14m above it to provide dispersed critical reflexes of 30 ms. In the final form the acoustic reflector resembles the shape of an ellipse positioned longitudinally, inclined 10 degrees above the horizontal. The stage canopy is composed of an aluminum and fiberglass ring, with folding panels in translucent polycarbonate.

4.2.3 Shape Optimization

4.2.3.1 Resonant String Shell

(37) *Resonant String Shell* is a hand-held, sustainable temporary acoustic shell, developed since 2011 and built during the architectural workshop at Villa Pennisi in Musica (Acireale), every year since 2012.

(38) Since 2012 *Gridshell.it*, the Acoustics Department of *Buro Happold Engineers* and the *Architecture Department* of University of Naples "*Federico II*" have developed the research program that concerns the design of an acoustic shell for outdoor music concerts from the room.

The research for the form was carried out through parametric modeling and multi-objective optimization algorithms. The geometric acoustic parameters have been analyzed through the image source technique and for the most performing solutions the Pareto coefficient has been taken as reference. The detailed acoustic simulation was then performed using more specific software. Finally, to verify the quality of the optimization process for musicians and the public, on-site measurements were taken.

The development of this structure raises the following main problems:

1. Difficulty of musicians to feel each other;
2. Poor listening experience for the public.

Considering the four types of concert halls defined by Barron based on the plan (Shoebox halls, Fan-Shaped halls, Vineyard hall, Hexagonal hall) in "*Auditorium Acoustics and Architectural Design*", the first concept of ReS was developed starting from a fan shape mixed with the silhouette of an old gramophone able to amplify and project the sound according to a certain directivity.

Figure 23 Grosser Musik Vereinsaal (Vienna). The side walls are irregular due to 40 windows, 20 doors above the balconies and 32 female, statues below. Thanks to the poor width and the interrupted surfaces, the immediate reflected sound reaches each place.

(44) *Rectangular-plan* concert hall (S*hoebox hall*): usually characterized by parallel and vertical side walls and a flat ceiling. Most of the historic halls are characterized by the presence of ornaments (sculptures, bas-reliefs and cornices) that tend to make the room assume a complex and irregular volume, guaranteeing a good level of sound diffusion / dispersion; in this way the sound waves are not reflected specularly by the surfaces but are diffused in many directions.

Concert hall fan: Compared to the previous ones it offers better visibility, however, especially when the wall that delimits the back is made up of a concave curve, it produces echo problems. To solve this problem, the solution is to reflect the sounds downwards, then towards the public. In these rooms there is no perception of being surrounded by sound: there is a more frontal than lateral sound and the reverberation is lower.

Figure 24 Lecture hall (Caracas). Distinctive feature of the room: "flying saucers"*. Fan-shaped with a curved roof and a rear wall with its center of curvature in the back of the stage. To solve the problems of echo and lack of uniformity in sound distribution, reflective panels have been added to cover a surface equal to 70% of the ceiling. Thanks to the sculptor Alexander Calder these are not just rectangular panels, but "flying saucers"*

Figure 25 St. David's Hall (Cardiff). Influenced by the Vineyard hall *of the Berlin Philarmonic. According to a research on the best eleven concert halls in England, this was close to having the best characteristics with regard to clarity, reverberation, intimacy and envelopment of the sound by the listeners. This is due to the high reverberation that allows an excellent sound diffusion.*

Hexagonal rooms: if the side walls are not parallel to each other but inclined they can provide sound reflections in the last places of the floor; in this way, after removing the area in front of the stage, all the positions of the audience take advantage of the first reflections.

The *vineyard halls* are characterized by a high number of seats and offer many acoustic advantages: good balance between clarity and reverberation, the possibility of first lateral reflections, a diffuse sound field, the possibility of having a greater width of the room at the same time and a public willing to surround the stage, furthermore some details can be modified independently of the rest of the room, leaving designers more flexibility.

Figure 26 Philarmonie Hall (Berlino).
The basic principle of the project is "To put music at the center". In fact, the architect Hans Scharoun argued that the normal arrangement of the orchestra at the end of the room prevented communication between the audience and musicians. This way no listener is further than 30m from the stage. The orchestra space is the lowest part of the room, so to spread the music evenly the cover has a convex shape. Seen in plan the room is symmetrical, but, seen from a lateral position it is asymmetrical. The orchestra area is not fixed but can be lowered or narrowed as needed. In front of the orchestra, in the audience section, the sound is clear and balanced. The only disadvantage is that spectators sitting at the back of the stage hear a different sound.

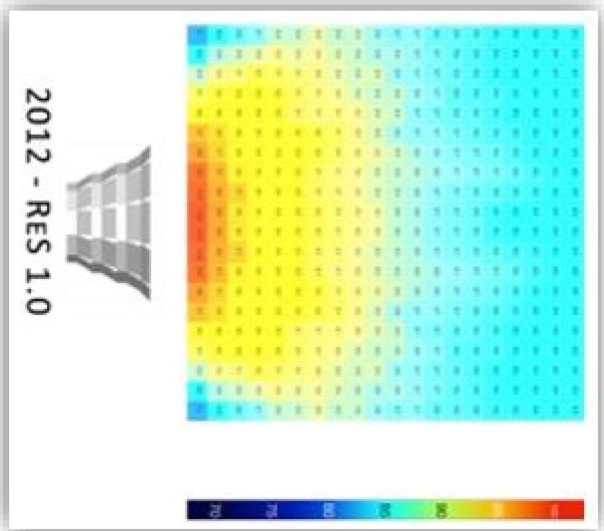
(38) The material chosen to make ReS is wood as this material is able to reflect sound without interfering with its quality; furthermore the realization is easy to build (with reversible joints) and economic.

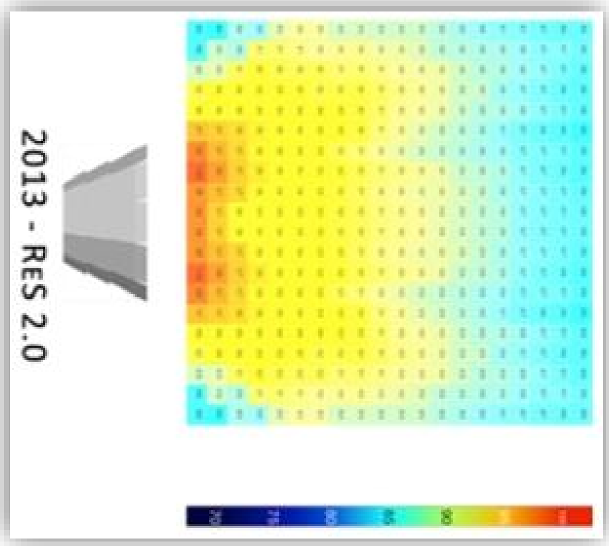
The system has a high degree of flexibility thanks to the fact that the panels are connected to the structure through a set of ropes; this allows to accurately adjust the inclination of each suspended panel based on the different settings.

The structure consists of four arched trusses in spruce slats, while the coating system is obtained by suspending poplar chipboard panels. (37) In particular it was developed starting from two different systems:

1. Spatial structure in wood that supports the internal surfaces, whose task is to reflect the sound towards the public. The first three prototypes were structured with four wooden portals composed of trusses, which decrease in height and length from the proscenium to the background. These polygonal portals are connected through a secondary triangular structure to obtain static indeterminacy and offer additional rigidity to the support elements;
2. Internal paneling hanging from the structure whose shape is defined by the inclination of the panels designed to offer a comfortable listening experience up to the last row of the public. The surface is made of chipboard, an inexpensive material capable of reflecting sound over a wide range of frequencies thanks to their weight.

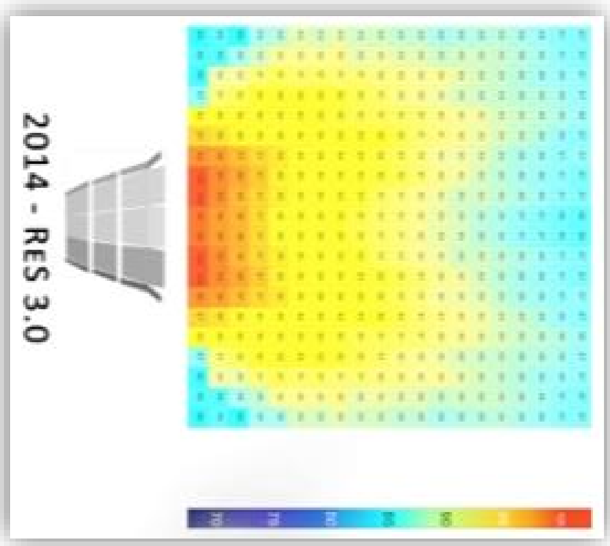
The *first prototype* (2012) consisted of three strips of rectangular panels suspended from the structure. To improve the acoustic response in the last lines of the public, overhanging panels have been fixed to the external portal. From the acoustic tests we note a problem concerning the loss of low frequencies caused by the triangular holes between the panels.





In the *second prototype* (2013) we tried to solve the problem concerning the loss of low frequencies by tightening the connection between the panels to eliminate the holes in the shell. Rectangular panels are transformed into trapezoids and wooden connections have been used instead of being fixed with ropes. To improve the response of medium-high frequencies, small suspended panels (size 50*60cm, spaced 3cm apart) have been used. Thanks to this expedient it has been possible to have a global improvement in the propagation of sound up to the most distant rows. In this prototype there are the following problems: loss of sound character, too strong response at low frequencies under the shell.

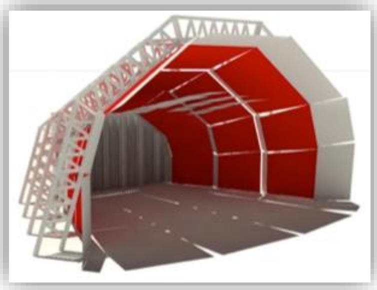
The *third prototype* (2014) sees an increase in the size of the structure; the stage depth reaches 420cm. The trapezoidal panels have been increased and three rows of small panels have been added in the middle (connected to the structure by means of ropes). To better spread the sound, a new device has been added in the background: a series of thin compensated blades interspersed with wooden elements with different sections (QRD diffuser). With this prototype the 2015 *Peter Lord Award* was won.



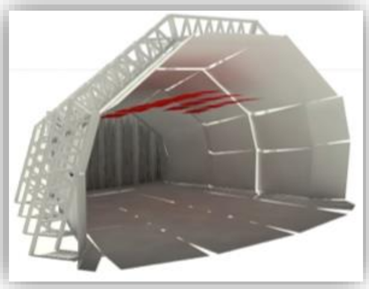
Considering the problems mentioned above, the design of this structure has three fundamental purposes:

1. Generate a uniform sound field on the musicians, then improve the ensemble and save the entire sound spectrum from any frequency cancellation event;
2. Increase the sound volume on the audience and improve the spatial perception;
3. Improve the apparent width of the source.

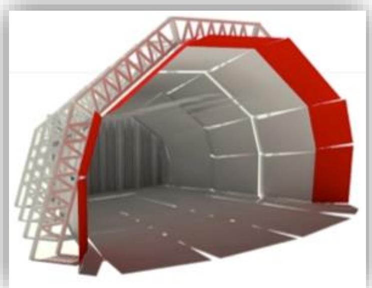
The acoustic machine is made up of four main acoustic subsystems designed to work together:



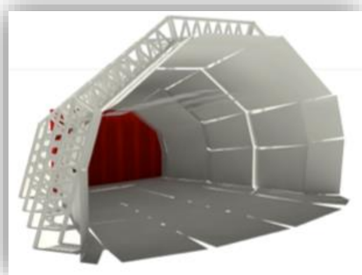
Main shell includes
larger exterior panels.



Matrix includes the
second series of panels.



Ciglia includes the
panels closest to the
public.



The *bottom of the scene*
corresponds to the deep
end of the shell.

The main purpose of the shell is to capture the acoustic energy of the instruments, which would otherwise be lost due to the variability of each of them in each band of frequencies, and project it on the public and on the stage. Particularly, we want to increase the first reflections. (27) According to *Lokki*, early broadband reflections, which preserve the temporal envelope of sound, contribute to clear and open acoustics with powerful bass. When the sound reaches the sides of the head, binaural hearing emphasizes the same frequencies produced by a greater orchestral dynamics, thus improving the perceived dynamic range.

(29) The characteristics of the initial sound depend very much on the shape of the room, while the energy of the late sound depends more on the average absorption of the room. The international standard ISO 3382-1 contains indexes that are insufficient to describe in detail the initial sound. Some authors have underlined the importance of some parameters:

- *Haas* underlined the importance of the first 30ms and the subjective perception of the volume;
- *Barron* studying the effects of a single first reflection from side walls and ceilings underlined the importance of the first lateral reflections;
- *Hidaka et al* underlined the importance of energy coming in the first 80ms. We note that in the successful rooms there is a high sound power in the first 80ms corresponding to a good amount of early reflections (reflections after 80ms are perceived by the listeners as enveloping energy).

The distribution of sound energy in space and over time poses a complex geometric problem, reflections must be directed in such a way as to provide sound energy uniformly in space and with intervals of time such as to satisfy subjective preferences.

(38) Generating an inhomogeneous increase in the SPL as well as improving the listening experience for the public (increase in perceived volume and control of sound dispersion in the entire frequency range), a basic support is created for musicians in order improve their listening skills. (37) Due to the strong symmetrical reflections (which must be controlled by the optimization of the inclination of the panels) inside the shell there is an increase in SPL and a non-uniform sound field.

(38) The shape of the shell derives from a process of improving the shape defined by three elements (the first two variables, the third constant):

1. *Emitters* (sources of acoustic simulation): standard sextets configuration. Each source is intended as an omnidirectional;
2. *Reflective panels* (the room of acoustic simulations): 21 reflective panels hinged to the structure through their front edge which corresponds to the axis of rotation. The angles correspond to the genome variables so, in this way, each element performs an independent rotation with the only constraint of a symmetrical structure to ensure a symmetrical acoustic response and a simpler installation in the construction phase;
3. *Target surfaces* (area of the public to be mapped): area of size 20 * 15m (considering 500 people), subdivided into 256 sub-areas.

The acoustic simulation was performed using the raytracing method using the Grasshopper *Sonic 4* plugin: the rays are projected directly towards the reflecting surfaces to calculate the first order of reflections.

As mentioned above the acoustic performance is measured based on two main objectives: the overall sound level and distribution on the public. Two fitness functions were used, corresponding to the total number of reflections reaching the public due to the increase in the overall sound level and their standard deviation. The multi-objective optimization process for these two functions was performed through the *Octopus* plugin. Finally the solutions have been verified through the analysis of the Pareto efficiency.

The array system provides three types of support:

1. Guide the mid-high frequencies to the public;
2. It helps the mutual listening ability of musicians;
3. Increases the level oc clarity of sound perception, reducing the time of the first high-frequency reflections.

Because, in this case, different compositions of emitters are considered (a quartet, a sextet, an octet and a 12-element orchestra) the array is used to try to provide an effective acoustic response for each formation allowing flexible use of the shell.

Acoustic test measurements, carried out to verify the design and acoustic simulations, are based on two main aspects of the acoustic project:

- Acoustic response to the public (typical room acoustics parameters were used as defined by EN ISO 9982-1);
- Acoustic response within the acoustic shell (based on the ensemble and on the mutual auditory performance for musicians).

Although initially based on the acoustic parameters used in the design of concert halls, these values cannot be used as reference values for outdoor simulations. In this case it was based on the comparison between the results obtained by the same measurements in empty conditions (therefore without the structure) and in conditions with the present structure. In particular, the following acoustic parameters were analyzed:

- *SPL* [dB]: *sound pressure level* in the position of the receiver, calculated with respect to the measurement of the free field of the source level at 10m;
- *C80* [dB]: *Clarity* corresponds to the targeted balance level between early energy and late energy, which arrives after 80ms of direct sound;
- *ST1* o ST_{early}[dB]: *Stage Support* corresponds to the measure of mutual listening and the performance of the ensemble on stage. In this case its optimal range is based on a small ensemble which prefers a greater presence of strong early reflections (a very high value of this parameter is expected);
- *Impulse response* identification of the beneficial support provided by the acoustic shell to the public in terms of additional preliminary reflections.

Comparing the results obtained in the two different configurations (without and with the structure) leads to the following conclusions:

- *SPL* [dB]: at each point of the receiver an increase of about 6dB was noticed (addition of useful reflections);
- *C80* [dB]: on average a 4-5dB increase was noted for each reception point. No late energy increase coming after 80ms;
- *ST1* falls within the set of values expected (average value between -24dB and -4dB. The interviewed musicians confirmed the subjective perception relative to this value.

There is a particular result in the combination with sextets: we can see reflections that arrive in the first 6ms after the direct sound.

4.2.3.2 Collisioni Festival

(39) Palma et al conducted a study to design an acoustic shell to be placed in the public square in Barolo (in the stage position) during the *Collisioni* festival.

During this project the acoustic potential of complex and doubly curved surfaces through the analysis of the parameter *Total Relative Level of the sound/Strength parameter* (*G*) was also studied. As a reference, the values proposed by Barron were taken into consideration, based on the source-receiver distance and the subsequent subjective judgments on the volume.

The main objective was energy optimization; considering the Barron curve as the minimum and maximum constraint for the values of the parameter G any value above the curve was considered a waste while those below were considered insufficient.

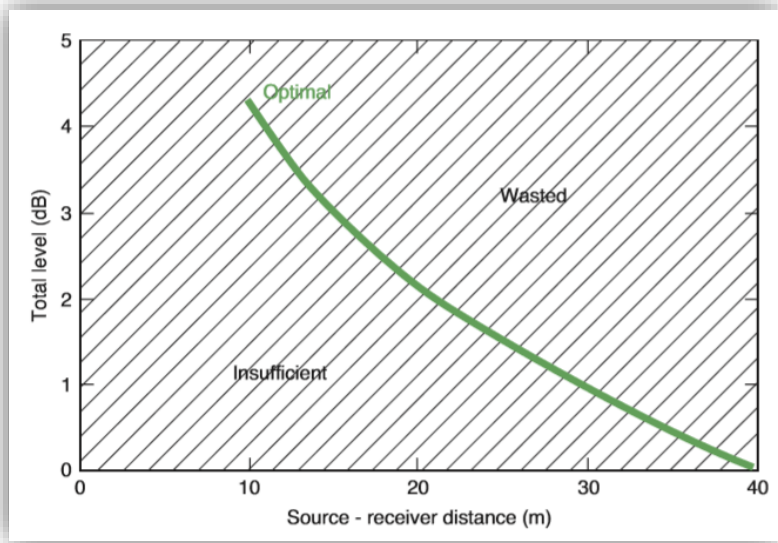


Figure 27 Barron's curve

Two simulation models have been produced. In the first one, the geometric evaluation of ray distribution uniformity was performed. The system consists of three parts: omnidirectional source, receiving surface (public) and reflective surface (acoustic shell). The latter consists of a series of points in the three-dimensional space in which the spatial coordinates of the points define the domain. The output of this model consists of the numerical count of the distribution of the rays on the receiving surface considering both the first order of reflection and the rays of the reflecting surface. By varying the coordinates of the points of the surface there is a morphological variation of the reflecting surface and therefore a different distribution of the sound beams on the receiving surface. The reflecting surface is parametrically generated from an ordered series of three-dimensional points, grouped in curvilinear clusters along the *X* direction. Each surface point has been considered the geometric center of a virtual square belonging to the *XZ* plane with a border length equal to a value defined by the user (each point was free to move by $\pm {}^{d}/_{2}$ along the *X* and *Z* axes. In this case *d* was set equal to 2m. Control points were within a volumetric constraint of 12mX14mX12m which It defined the global search space. The second model was used to make physically reliable acoustic simulations, and through the *Pachyderm* plugin it was possible to simulate real acoustic conditions, considering the depth of stage equal to 12m and length equal to 14m (total area of coverage equal to $146m^2$. The reception area is equal to $1200m^2$. The omnidirectional source was positioned at 1.25m from the b front stage of the stage, the density of the receivers has been set to 1 every 3m2 with a height of 1.70m (considering the audience standing). The settings for ray tracing were as follows: 500000 rays, 2000ms cutting time, reflection order on 1. Total receivers 380.

From the results we note that in this case the concave elements are the best performing solution for passive acoustics in outdoor environments or without reflection. The concave forms serve to eliminate the phenomena of acoustic focusing; while the convex shapes serve the quantities of energy available and the simultaneous absence of a built fence.

5. THE CHOIR OF THE POLYTECHNIC

Figure 28 The choir of the Polytechnic of Turin (40)

(40) The choir of Polytechnic, *Polietnico*, was founded in December 2013 following a singing workshop organized by two professors from the Department of Mathematical Sciences of the Polytechnic University of Turin with 30 students participating. Supported by the Polincontri association, the activity grows to reach 121 elements among students, professors, researchers and employees of the Polytechnic.

The project has a strong international connotation thanks to the many foreign students (36%) regularly enrolled at the Politecnico or included in Erasmus or Double Degree programs. This multi-ethnicity is reflected in the repertoire, in which genres, languages and sounds of all continents are touched.

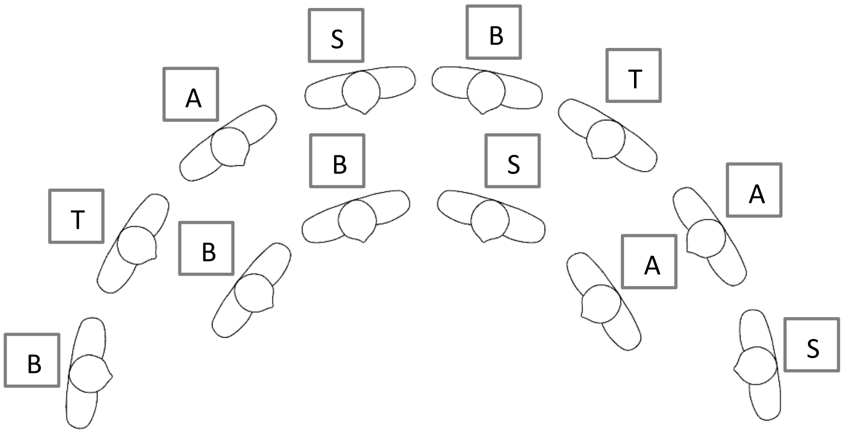
The artistic direction is entrusted to the two choir directors: M. Giorgio Guiot and Dario Ribechi.

Figure 29 Sedicetto

Among the active projects there is the *Sedicetto*, a chamber group with reduced staff.

6. Project

Twelve choristers took part in the measurements: three Sopranos, three Altos, two Tenors and four Basses. At the choice of the conductor, four choristeres, one per section, wore connected binaural microphones, each one for a recorder. Measurements were carried out in two contexts: in an external environment and in an internal environment. In particular, the external condition took place in the inner courtyard of the Polytechnic of Turin (on the Corso Duca degli Abruzzi side) while the internal one in the *"Giovanni Agnelli" Aula Magna*. As can be seen from the image below, the chosen formation follow the mixed one (except for the presence of the two basses in the front row).



This choice was made considering the data reported by Aspaas, McCrea, Morris, Fowler in *"Select Acoustic and Perceptual Measures of Choral Formation"*: to the question "Ease of hearing others", the mixed formation was the one that obtained the highest score.

Choral Formation	Vocal Part (N)	Ease of Production	Sound of Choir	Ease of Blending With Section	Ease of Hearing Others	Prefer Singing
Block						
	Soprano (8)	8.07 (2.10)	7.08 (1.61)	6.76 (3.04)	5.78 (2.61)	5.89 (2.18)
	Alto (10)	8.13 (1.83)	7.10 (1.88)	8.39 (1.71)	5.75 (2.30)	6.20 (2.76)
	Tenor (5)	8.77 (1.06)	6.05 (2.88)	6.71 (3.45)	5.23 (4.16)	6.22 (3.56)
	Bass (7)	7.99 (1.42)	6.80 (1.70)	7.62 (1.62)	5.83 (1.83)	6.63 (1.55)
Mixed						
	Soprano (8)	5.28 (2.60)	7.69 (2.22)	6.00 (2.89)	7.10 (3.52)	7.21 (3.35)
	Alto (10)	7.23 (2.55)	6.80 (2.34)	6.20 (2.93)	9.20 (0.73)	8.68 (1.60)
	Tenor (5)	6.42 (3.52)	6.51 (3.64)	6.05 (3.34)	8.13 (3.88)	7.09 (3.77)
	Bass (7)	5.01 (1.94)	6.26 (3.38)	2.82 (2.58)	8.63 (1.60)	6.94 (3.43)
Column						
	Soprano (8)	6.81 (2.99)	4.08 (2.13)	5.78 (3.40)	2.39 (2.20)	3.73 (3.88)
	Alto (10)	7.56 (2.38)	5.68 (1.69)	7.18 (2.18)	4.80 (2.78)	4.55 (2.61)
	Tenor (5)	8.38 (1.6)	7.81 (1.96)	8.68 (2.33)	6.22 (3.21)	6.57 (3.91)
	Bass (7)	9.64 (0.23)	8.66 (1.62)	9.36 (0.75)	6.04 (2.74)	8.66 (0.97)

Figura 30 Chorus preferences regarding the three types of choral formations (14)

As for spacing, however, close spacing has been chosen as the choir may not always be able to perform with greater spacing. The spacing adopted in the two environments are shown in the following images.

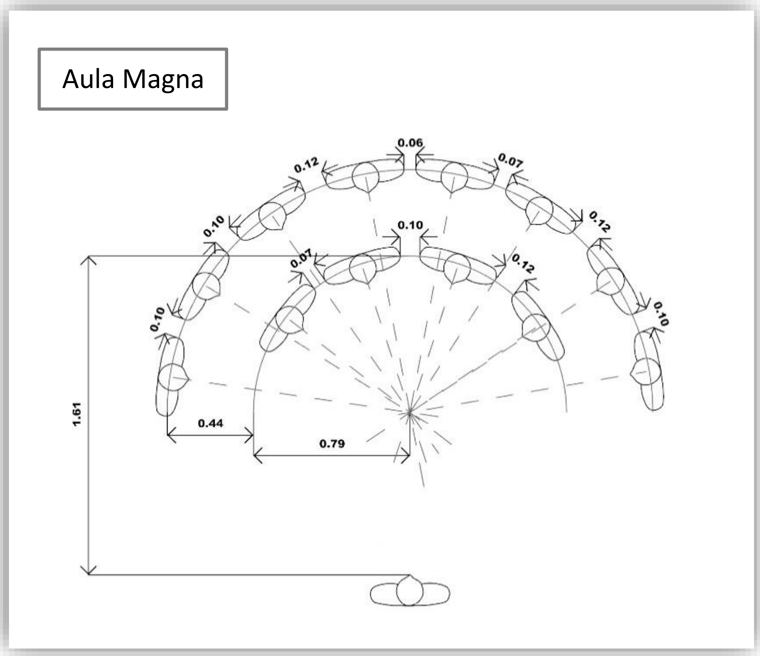


Figure 31 Spacing adopted in measurements made in the Aula Magna (m)

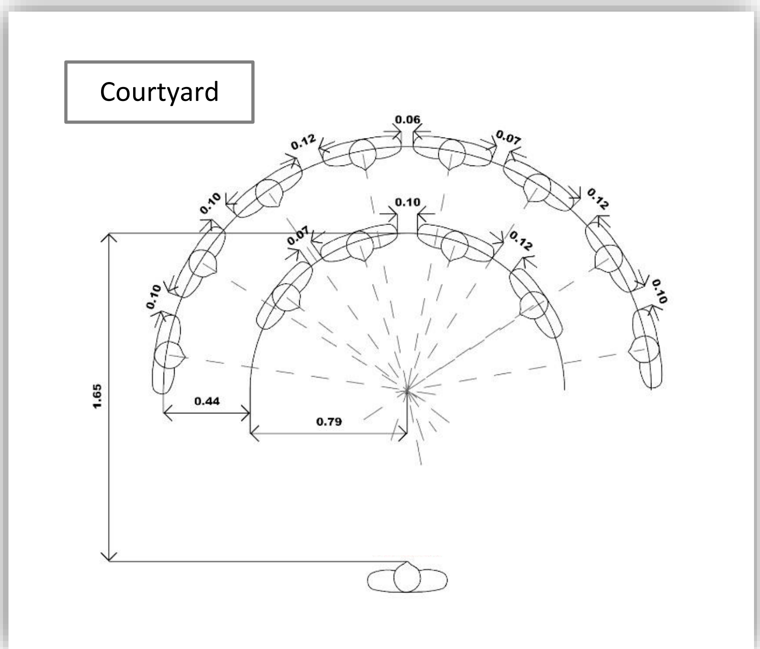


Figura 32 Spacing adopted in measurements made in the courtyard (m)

6.1 Measurement setup

While maintaining the mixed formation, choristers were asked to chainge their posizion. For this reason, in both environments, four measurement configurations were carried out. The positions adopted are represented in the following figures (red-underlined choristers have worn binaural microphones).

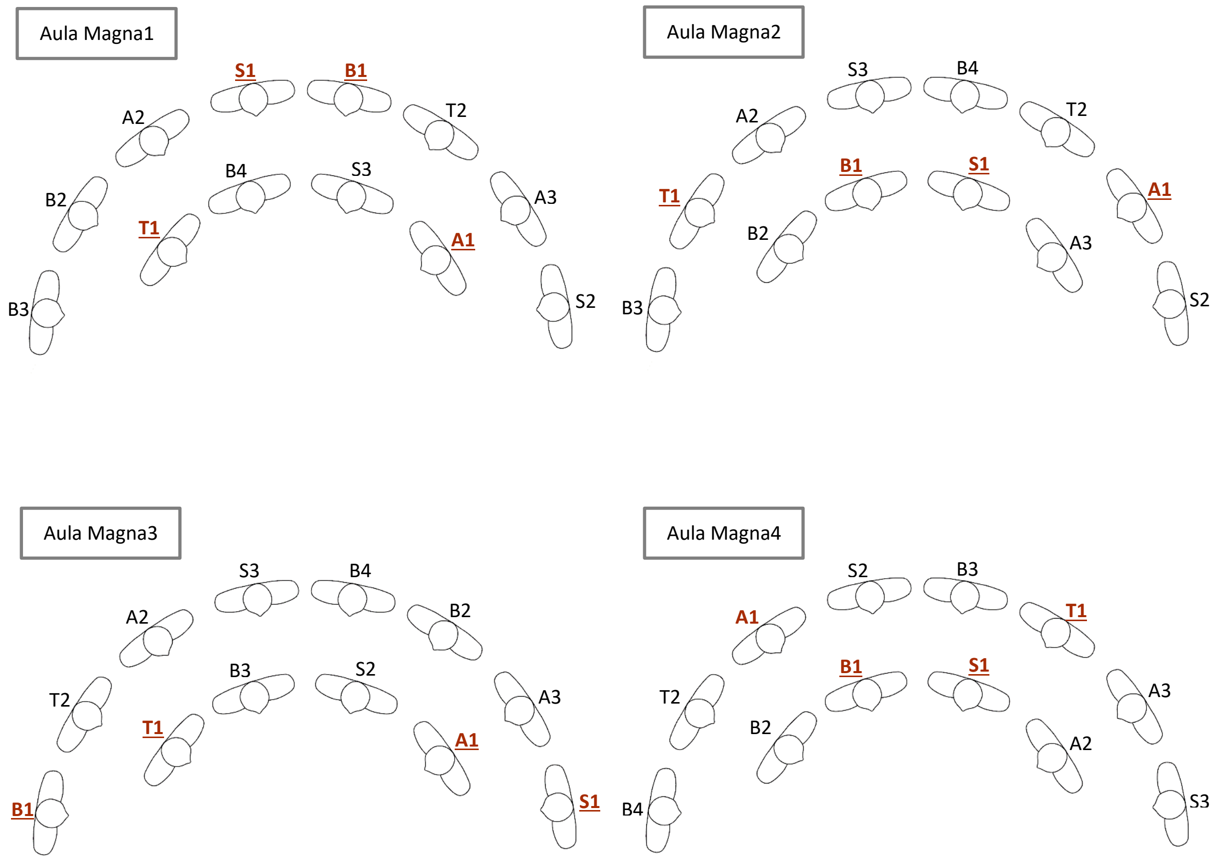


Figura 33 Positioning of the singers in the measurements made in the Aula Magna

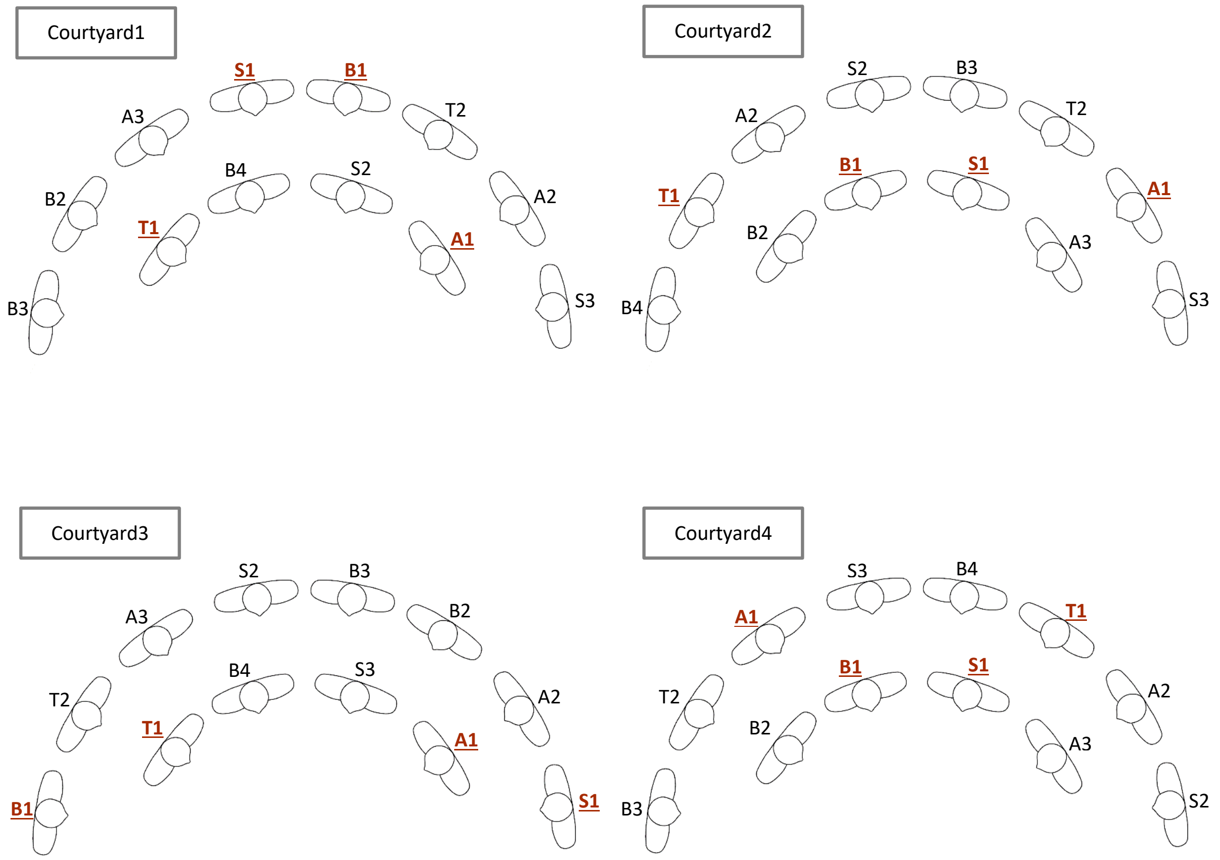


Figura 34 Positioning of the singers in the measurements made in the courtyard

Each measurement includes the following three conditions:

1. *"Tutti condition"* all the singers sing together;
2. *"Solo condition"* only the singer with binaural microphones sings;
3. *"Silence condition"* all the singers sing except the one who wears binaural microphones.

The initial record level of the recorders has been set to 60dB. All the measurements were recerded in two *wav* files at *48kHz*: in the first one the configurations were recorded in the courtyard, while in the second those in the Aula Magna.

The microphones were attached with medical tape to the outer end of the singer's ear, making sure it didn't affect listening.

The software used to analyze the data were: *Audacity* (to cut the files and create those of the single measurements) and *Matlab* (to carry out the actual analysis and obtain the SOR).

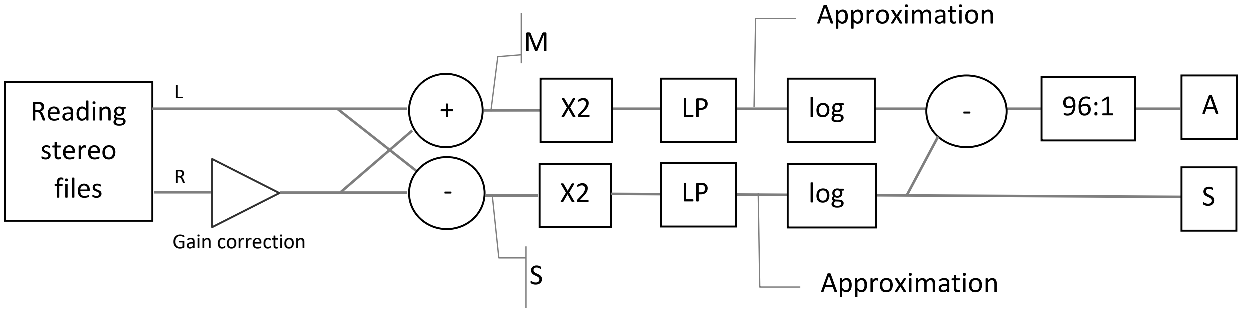
At the end of each measurement, each chorister was given a questionnaire consisting of three parts: the first part consisting of general data; the second included specific questions regarding the configuration just performed; the third, instead, included questions of comparison between the four configurations.

6.2 DATA ANALYSIS

The procedure performed with the script in *Matlab* was the following:

1. *Gain correction*: to allow the effective cancellation of the *"Self"* signal in *S*, the small gainvariations between the left and right microphones deriving from a position asymmetry must be canceled. The *"Solo Condition"* was registered for this very reason. Analyzing this recording through a cycle, the discrepancy between the two channels was found and the correction factor to be applied to the file for the parameter measurement was calculated, the *"Tutti Condition"*. The correction factor was calculated by making an approximation of 0.01.
2. Signal formation *S* and *M*. The first corresponding to the subtraction of the right channel from the left channel, determines the *Other* signal; the secondo, instead, corresponding to the sum between the left and the right channel, determines the signal *Self*.
3. Square of *S* and *M*.
4. Application of a second order low pass filter with 5Hz cutoff frequency.
5. Approximation of values less than or equal to zero at the minimum positive value of the signal. Through a cycle the values less than or other to zero have been seto equal to 50 (value out of range). Since the signal in this way was composed only of positive numbers, the minimum was found. Thus the values equal to 50 have been set equal to the minimum found.
6. Log-conversion of the two signal.
7. Sub-sampling of the two signals from 48kHz to 0.5kHz.
8. At the end we find the A contour through the subtraction of the two signals (AContour= $M - S$). This value corresponds to SOR+3dB.

The scheme executed can be represented in this way.



The same procedure was also applied to the *"Solo Condition"* and to the *"Silence Condition"*. In the first case it allows to determine the inflence of room reverberations (they are considered as *Other* signal).

The figure below show an example of *A Contour* and of the signal *S* in the *"Tutti Conditon"* and in the *"Solo Condition"* in the two environments.

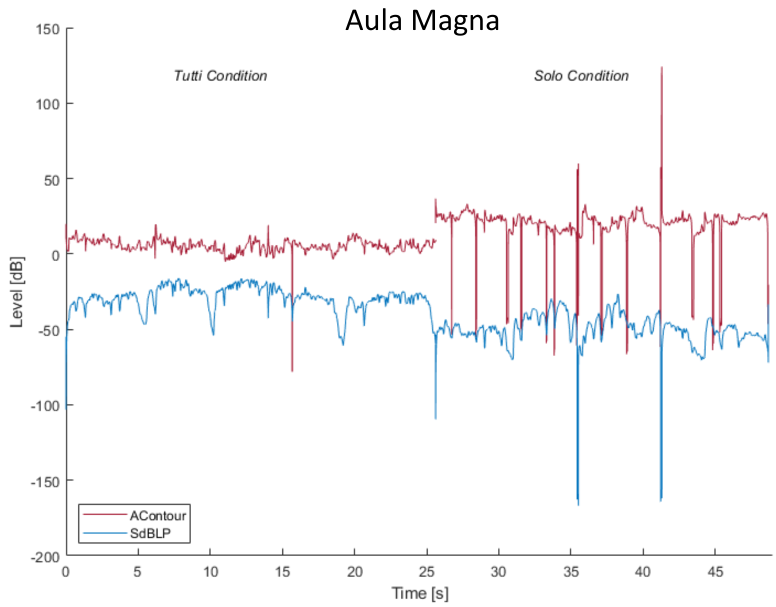


Figure 35 First configuration of the Alto section carried out in the Aula Magna, "Tutti Condition" and "Solo Condition". The red line corresponds to the A Contour (or SOR+3dB). The blue one, at the bottom, represents the S signal (level of Other + 3dB). On the x-axis the time is shown in seconds, while on the y-axis the level in dB.

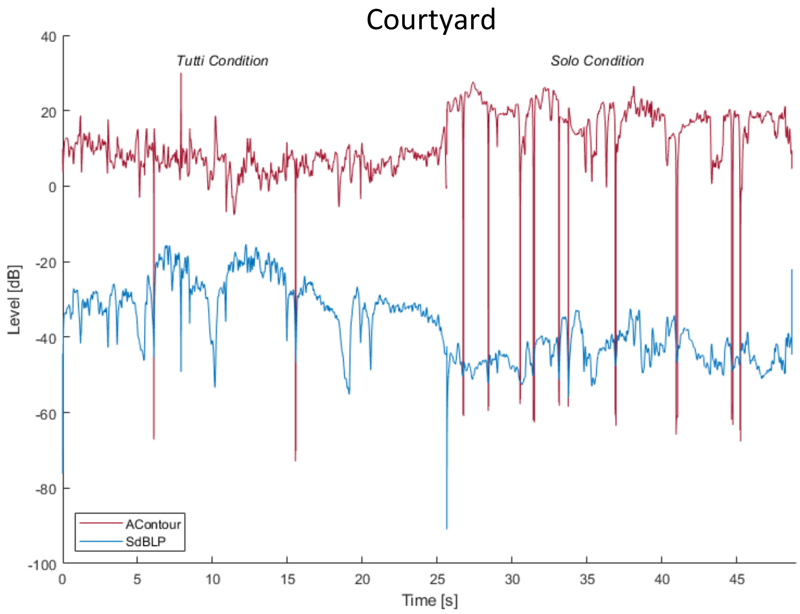


Figure 36 First configuration of the Alto section carried out in the courtyard, "Tutti Condition" and "Solo Condition". The red line corresponds to the A Contour (or SOR+3dB). The blue one, at the bottom, represents the S signal (level of Other + 3dB). On the x-axis the time is shown in seconds, while on the y-axis the level in dB.

To eliminate any silences and unwanted peaks (which could have been determined by the approximation made at the fifth point) it was decided to establish a threshold starting from the histogram of S (determined taking as a limit a frequency density lower than 150) after the conversion into decibels. This was then applied to both *S* and *M* before finding the *A Contour* and then before calculating the *SOR*.

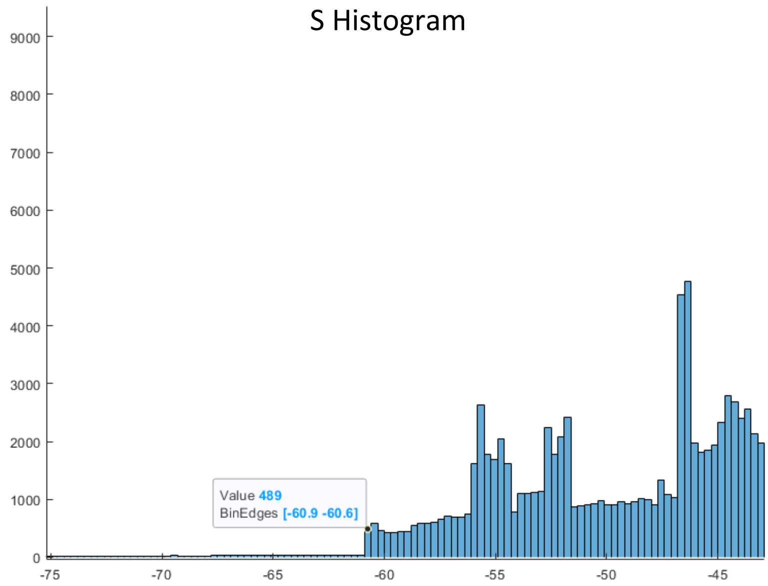


Figure 37 S histogram of the first configuration of the Alto section in the Aula Magna; "Tutti Condition". Considering the first value of y-axis greater than 150 (in this case 489) the corresponding threshold is -60.9dB.

The figure below show an example of *A Contour* and of the signal *S* in the *"Tutti Conditon"* and in the *"Solo Condition"* in the two environments after applying the threshold.

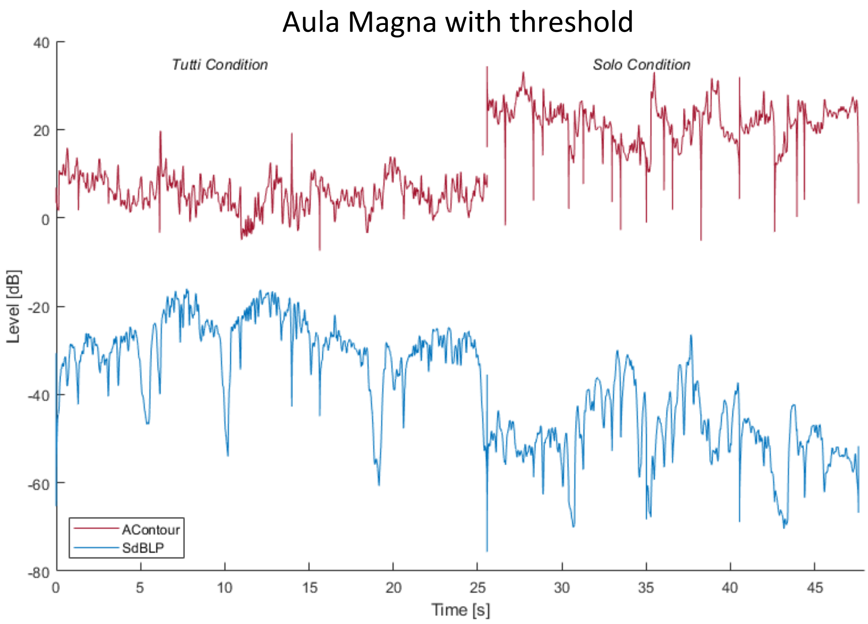


Figure 38 First configuration of the Alto section carried out in the Aula Magna, "Tutti Condition" and "Solo Condition". The red line corresponds to the A Contour (or SOR+3dB) after applying the threshold. The blue one, at the bottom, represents the S signal (level of Other + 3dB) after applying the threshold. On the x-axis the time is shown in seconds, while on the y-axis the level in dB.

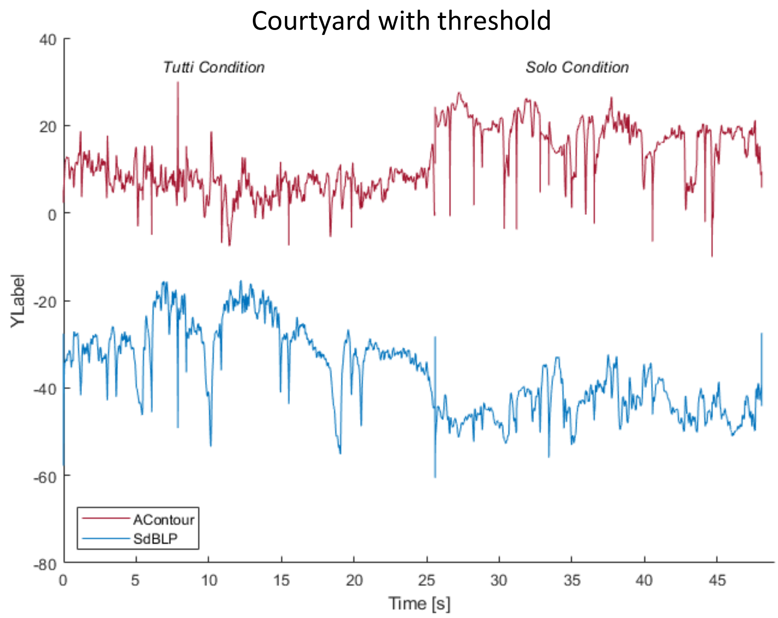


Figure 39 First configuration of the Alto section carried out in the courtyard, "Tutti Condition" and "Solo Condition". The red line corresponds to the A Contour (or SOR+3dB) after applying the threshold. The blue one, at the bottom, represents the S signal (level of Other + 3dB) after applying the threshold. On the x-axis the time is shown in seconds, while on the y-axis the level in dB.

6.3 Results

In this chapter the results will be presented and anlyzed, initially those without the use of the treshold and then those with the application of the threshold.

6.3.1 Results (No threshold)

6.3.1.1 Aula Magna

Four configurations were made to measure SOR in different positions. The resulting values are shown in the following table and in the graph below (which also shows the standard deviations).

SOR	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+7.11	+6.06	+7.93	+6.10	+6.80
Alto	+2.41	+2.75	+2.49	+3.91	+2.89
Tenor	+3.22	+2.96	+2.80	+2.85	+2.96
Bass	+0.36	**-0.43**	+3.11	**-0.18**	+0.71
Avg	+3.27	+2.83	+4.08	+3.17	+3.34

Table 15 SOR values per section found in the four configurations carried out in the Aula Magna; "Tutti Condition". This is the result without the application of the threshold

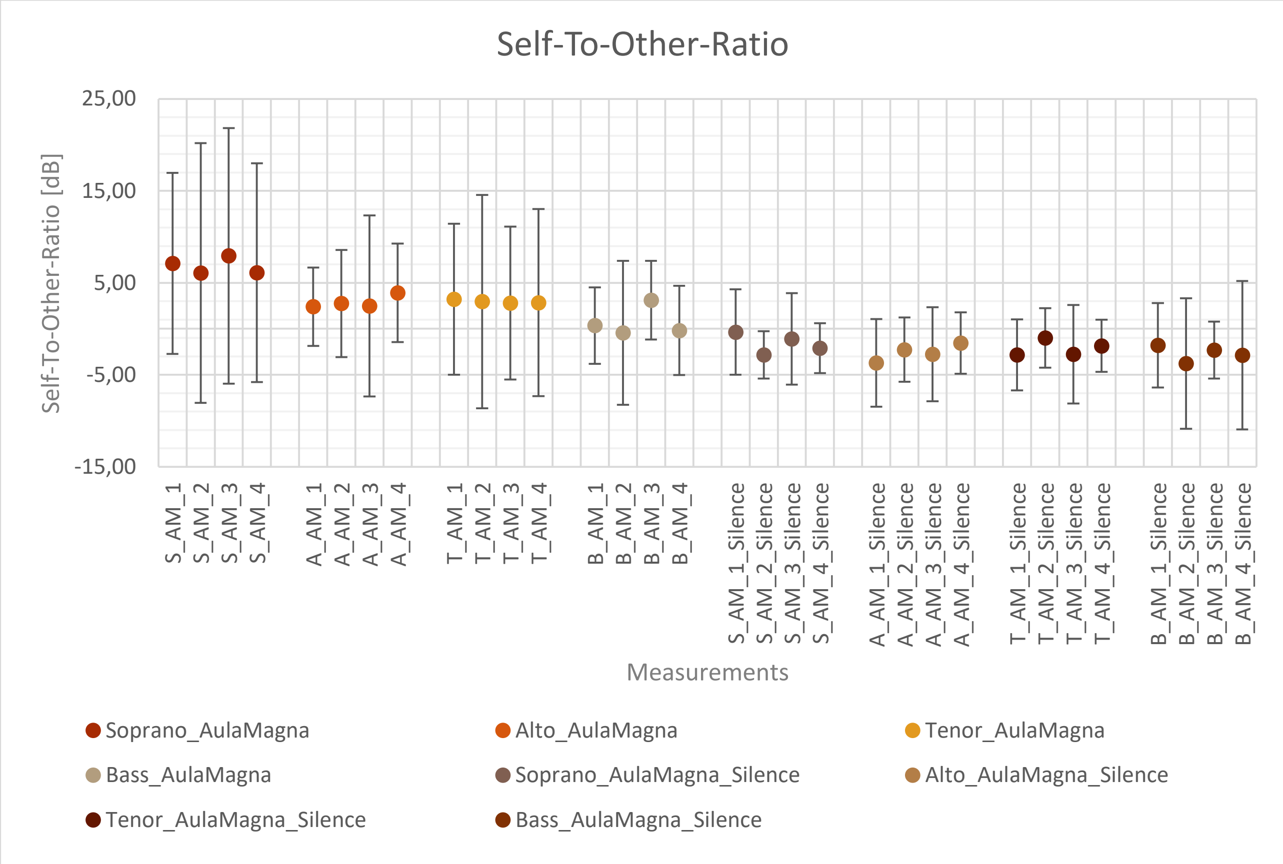


Figure 40 Self-To-Other-Ratio of the four configurations per subject. The first four series refer to the values of the "Tutti Condition", while the last four refer to the "Silence Condition". The bars indicate the standard deviations of the distributions.

Considering the graph above, in the "Tutti Condition", we have the following results (on average): +6.80dB for the Soprano (with extremes ranging from +6.06dB, in the second measurement, to +7.93dB, in the third measurement); +2.89dB for Alto (with extremes ranging from +2.41dB, in the first measurement, to +3.91dB, in the fourth measurement); +2.96dB for Tenore (with extremes ranging from +2.80dB, in the third measurement, to +3.22dB, in the first measurement) and +0.71dB for bass (with extremes ranging from -0.43dB, in the second measurement, to +3.11dB, in the third measurement). It is noted that in all measurements the Soprano has a SOR which is clearly greater than that of the others; The bass, on other hand, in two measurements has a value less than zero. On average, the SOR value in the Grat Hall is +3.34dB.

Considering the standard deviations, the following values are found: Soprano +12.43dB, Alto +6.32dB, Tenor +5.28dB and Bass +8.01dB. Also in this case we note that the Soprano has higher values than the other sections. On average the resulting value is +8.01. The table below summarizes in detail the values of this parameter for the various sections and measurements.

Dv.Std_Tutti	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+9.84	+14.12	+13.88	+11.89	+12.43
Alto	+4.26	+5.83	+9.83	+5.36	+6.32
Tenor	+8.20	+11.61	+8.31	+10.18	+5.28
Bass	+4.15	+7.83	+4.27	+4.85	+8.01

Table 16 Standard deviations of the four configurations carried out in the Aula Magna based on the four sections ("Tutti Condition")

Considering the figure 40 “Self to Other Ratio”, the last four series refer to the SOR in the “Silence Condition” (they are named with the *Silence* target). These values represent the method for detecting the *Self*. To have a proper discrimination between the two signals *Self* and *Other*, only these values should be less than 0. As was pointed out before however in our measurements also two values of the “Tutti Condition” result less than zero: -0.43dB and -0.18dB, respectively yhe second and fourth measurements of the bass.

In the table below shows the values of the “Silence Condition” based on the various configurations. On average we have the following results: -1.60dB for the Soprano (with extremes ranging from -2.84dB, in the second measurement, to -0.36dB, in the first measurement); -2.58dB for Alto (with extremes ranging from -3.71dB, in the first measurement, to -1.55dB, in the fourth measurement); -2.11dB for Tenor (with extremes ranging from -2.84dB, in the first measurement, to -1.00dB, in the second measurement) and -2.69dB for Bass (with extremes ranging from -3.78dB, in the second measurement, to -1.79dB, in the first measurement); for a total average of -2.24dB.

Silence	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	-0.36	-2.84	-1.09	-2.11	-1.60
Alto	-3.71	-2.27	-2.77	-1.55	-2.58
Tenor	-2.84	-1.00	-2.77	-1.85	-2.11
Bass	-1.79	-3.78	-2.31	-2.87	-2.69
Avg	-2.17	-2.47	-2.23	-2.09	-2.24

Table 17 Values of the various configurations, in Aula Magna, for the “Silence Condition”.

The standard deviations of this condition give us an indication of the margin of error of the measurement under certain circumstances. On average we have a value of +4.36dB.

The “Solo Condition” gives us the SOR value with respect to the room reverberation. This condition, as mentioned above, was measured when only the chorister wearing binaural microphones sang. The following table summarizes the values of the individual configurations by section.

Solo	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+11.26	+10.95	+14.42	+12.32	+11.74
Alto	+16.27	+12.81	+14.95	+13.70	+14.43
Tenor	+16.40	+13.66	+16.30	+14.46	+15.21
Bass	+15.21	+17.31	+17.77	+15.33	+16.40
Avg	+14.79	+13.68	+15.36	+13.95	+14.45

Table 18 Values of the various configurations, in Aula Magna, for the “Solo Condition”.

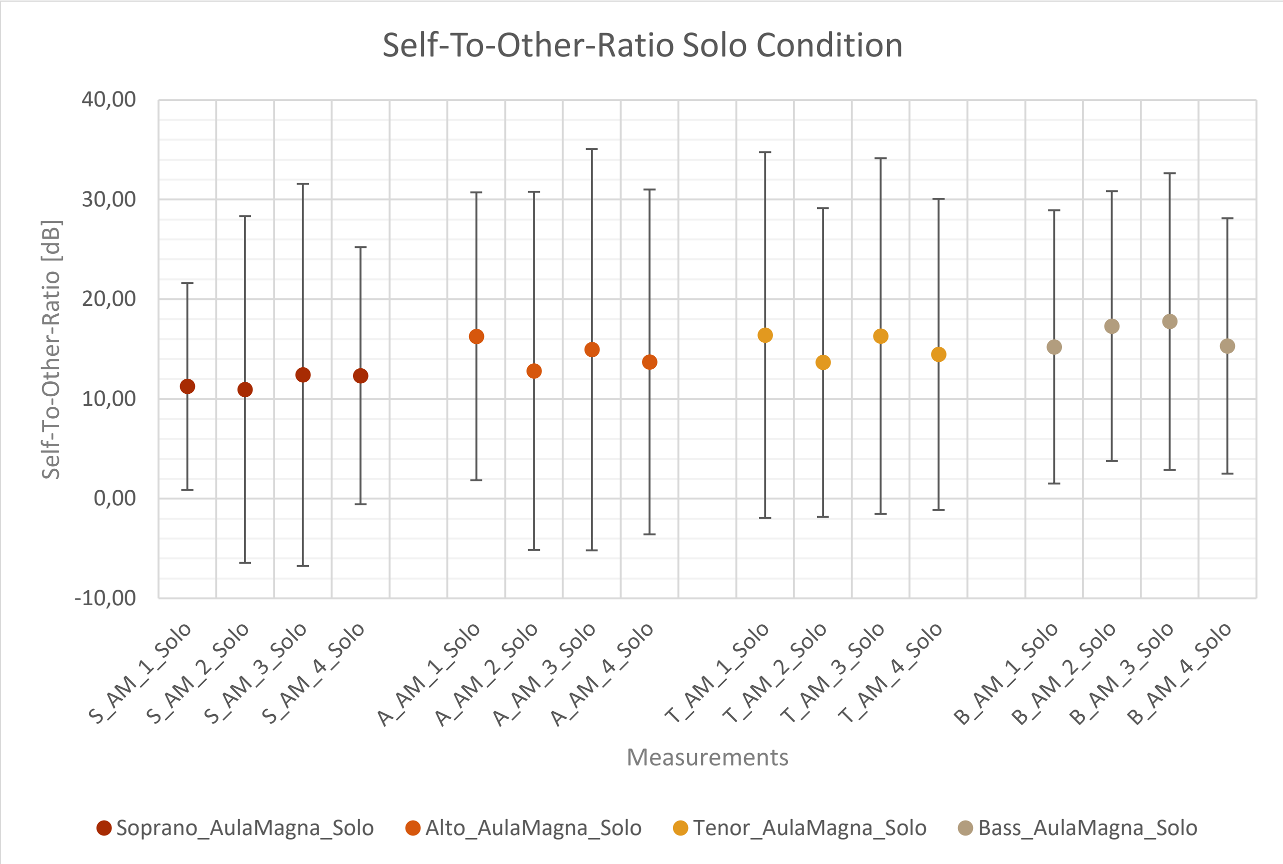


Figure 41 Self-To-Other-Ratio of the four choristers in the "Solo Condition". The lines correspond to the dtandard deviations of the ditributions.

In this case, on average, the following results are found: +11.74dB for the Soprano (with extremes ranging from +10.95dB to +12.42dB, respectively for the second and third measurements); +14.43 for Alto (with extremes ranging from +12.81dB, in the second measurement, to +16.27dB, in the first measurement); +15.21dB for Tenor (with extremes ranging from +13.66dB to +16.40dB, also in this case, respectively for the second and first measurements) and +16.40dB for Bass (with extremes ranging from +15.21dB, in the first measurement, to +17.77dB, in the third measurement). We note that unlike the other cases the soprano is the one that has the lowest values. The total average appears to be of +14.45dB with extremes ranging from +10.95dB (soprano, second measurement) to +17.77dB (bass, first measurement).

Taking into consideration the values found in the "Tutti Condition" and in this we derive the relationship between the diffuse fiels of reflections in the room of one's voice and the sound of the choir. The following table shows the relative differences based on the various configurations.

Difference	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+4.16	+4.89	+4.49	+6.22	+4.94
Alto	+13.86	+10.06	+12.46	+9.79	+11.54
Tenor	+13.18	+10.71	+13.50	+11.62	+12.25
Bass	+14.85	+17.74	+14.66	+15.51	+16.40
Avg	+11.51	+10.85	+11.28	+10.78	+11.11

Table 19 Difference between "Solo Condition" and "Tutti Condition" in the various configurations. Relationship between the diffuse field of room reflections and the sound of the choir

On average the difference found is +11dB (with extremes ranging from +4.16dB, for Soprano, to +15.69dB for bass). It can therefore be said that the diffuse field of reflections in the room of one's voice is at leas 11dB weaker than the sound of other choristers: the choir masks the reflections if singer's voice.

6.3.1.2 Internal courtyard of the Polytechnic, Corso Duca degli Abruzzi side

The same procedure adopted in the Aula Magna was also carried out in the internal courtyard of the Polytechnic.

In the following table and in the graph below we can summarize the values of the Self-To-Other-Ratio of the four configurations for the four microphoned choristers.

SOR	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+5.10	+4.33	+7.27	+5.23	+5.48
Alto	+3.78	+4.27	+2.93	+4.20	+3.79
Tenor	+2.93	+3.85	+2.14	+5.54	+3.62
Bass	+2.49	+0.59	+3.71	+0.44	+1.81
Avg	+3.58	+3.26	+4.01	+3.85	+3.68

Table 20 SOR values per section found in the four configurations carried out in the courtyard; "Tutti Condition".

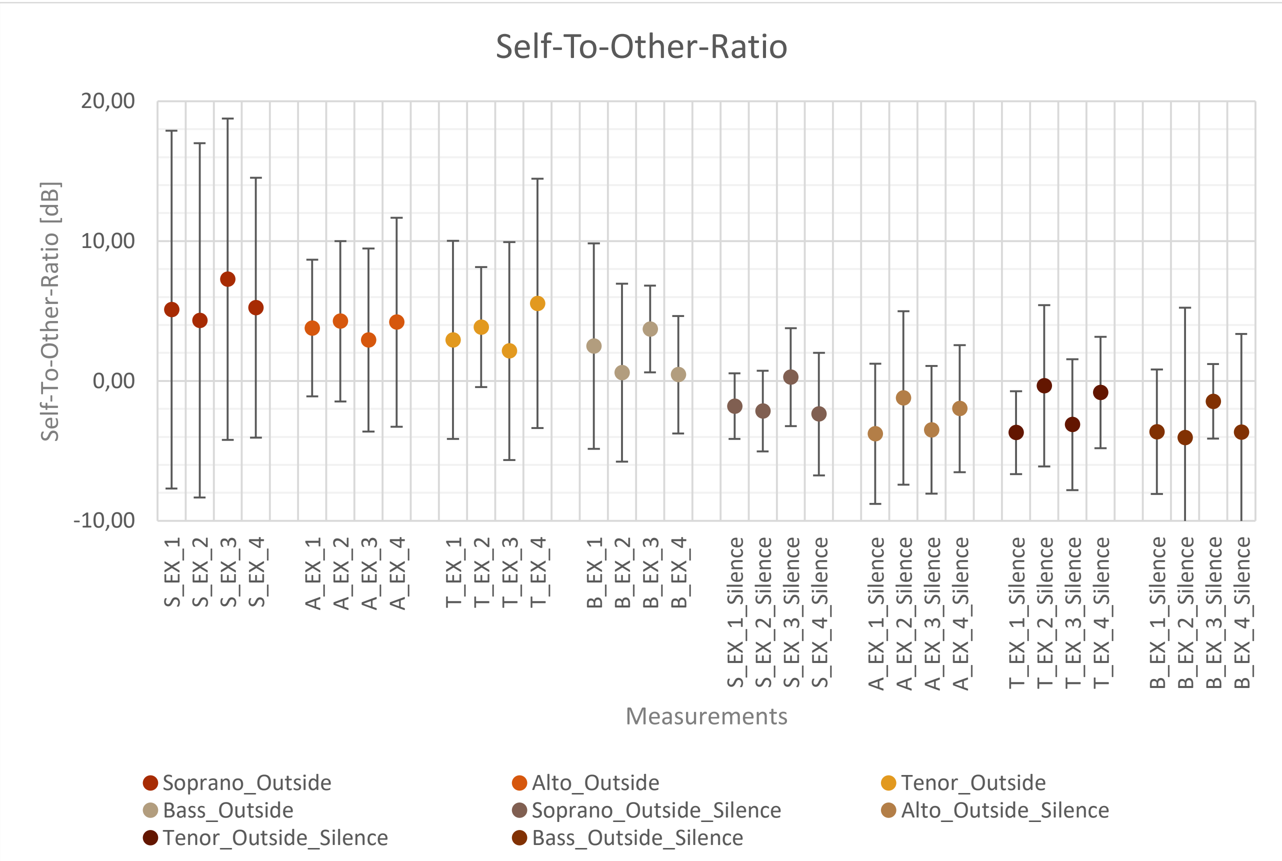


Figure 42 Self-To-Other-Ratio of the four configurations per subject, external condition. The first four series refer to the values of the "Tutti Condition", while the last four refer to the "Silence Condition". The bars indicate the standard deviations of the distributions.

Also in this case we start with the consider the SOR value, on average, of the various sections: +5.48dB for Soprano (with extremes ranging from +4.33dB, in the second configuration, to +7.27dB, in the third configuration); +3.79dB for Alto (with extremes ranging from +2.93dB, in the third configuration, to +4.27dB, in the second configuration); +3.62dB for Tenor (with extremes ranging from +2.14dB, in the third configuration, to +5.54dB, in the fourth configuration) and +1.81dB for Bass (with extremes ranging from +0.44dB, in the fourth configuration, to +3.71dB, in the third configuration); for a total average of +3.68dB. Also in this case we note that in most measurements the Soprano has a SOR value reater than that of the other sections (except for the measurement number four in which the SOR is of the tenor). Unlike the measurements made in Aula Magna, all the values are greater than zero.

Considering the standard deviationr, on average, we have the following values: Soprano +11.56; Alto +6.16; Tenor +7.02 and Bass +5.25 for a total average of +7.50. Also in this case we note that, in all configurations, the standard deviations of the Soprano are clearly greater than those of the other sections. Detailed values are shown in the following table.

Dv.Std_Tutti	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+12.79	+12.67	+11.48	+9.28	+11.56
Alto	+4.88	+5.72	+6.55	+7.47	+6.16
Tenor	+7.08	+4.29	+7.79	+8.92	+7.02
Bass	+7.34	+6.36	+3.10	+4.20	+5.25

Table 21 Standard deviations of the four configurations carried out in the courtyard based on the four sections ("Tutti Condition")

Considering, instead, the measurements made in “Silence Condition”, we immediately notice that, unlike those in the Aula Magna, not all the values are less than zero. In fact, in the third measurement the value of the Soprano is greater than zero, +0.27dB. Looking at the standard deviation there is an error margin of +3.50.

Silence	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	-1.81	-2.16	**+0.27**	-2.37	-1.52
Alto	-3.78	-1.22	-3.50	-1.98	-2.62
Tenor	-3.70	-0.35	-3.12	-0.82	-2.00
Bass	-3.64	-4.05	-1.47	-3.67	-3.21
Avg	-2.17	-2.47	-2.23	-2.09	-2.33

Table 22 Values of the various configurations, in courtyard, for the “Silence Condition”.

As can be seem from the table above, on average, we have the following values: -1.52dB for Soprano (with extremes ranging from -2.37dB, in the fourth configuration, to +0.27dB, in the third configuration); -2.62dB for Alto (with extremes ranging from -3.78dB, in the first configuration, to -1.22dB, in the second configuration); -2.00dB for Tenor (with extremes ranging from -3.70dB, in the first configuration, to -0.35dB, in the second configuration) and -3.21dB for Bass (with extremes ranging from -4.05dB, in the second configuration, to -1.47dB, in the third configuration); for a total average of -2.33dB.

Considering the “Solo Condition” the results are shown in the following table and in the graph below (in this the relative standard deviations are also shown).

Solo	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+11.12	+10.44	+13.17	+11.51	+11.56
Alto	+13.06	+12.54	+17.34	+13.70	+14.16
Tenor	+13.12	+7.06	+10.13	+13.93	+11.06
Bass	+11.97	+12.65	+17.86	+18.08	+15.14
Avg	+12.32	+10.67	+14.63	+14.30	+12.98

Table 23 Values of the various configurations, in courtyard, for the “Solo Condition”.

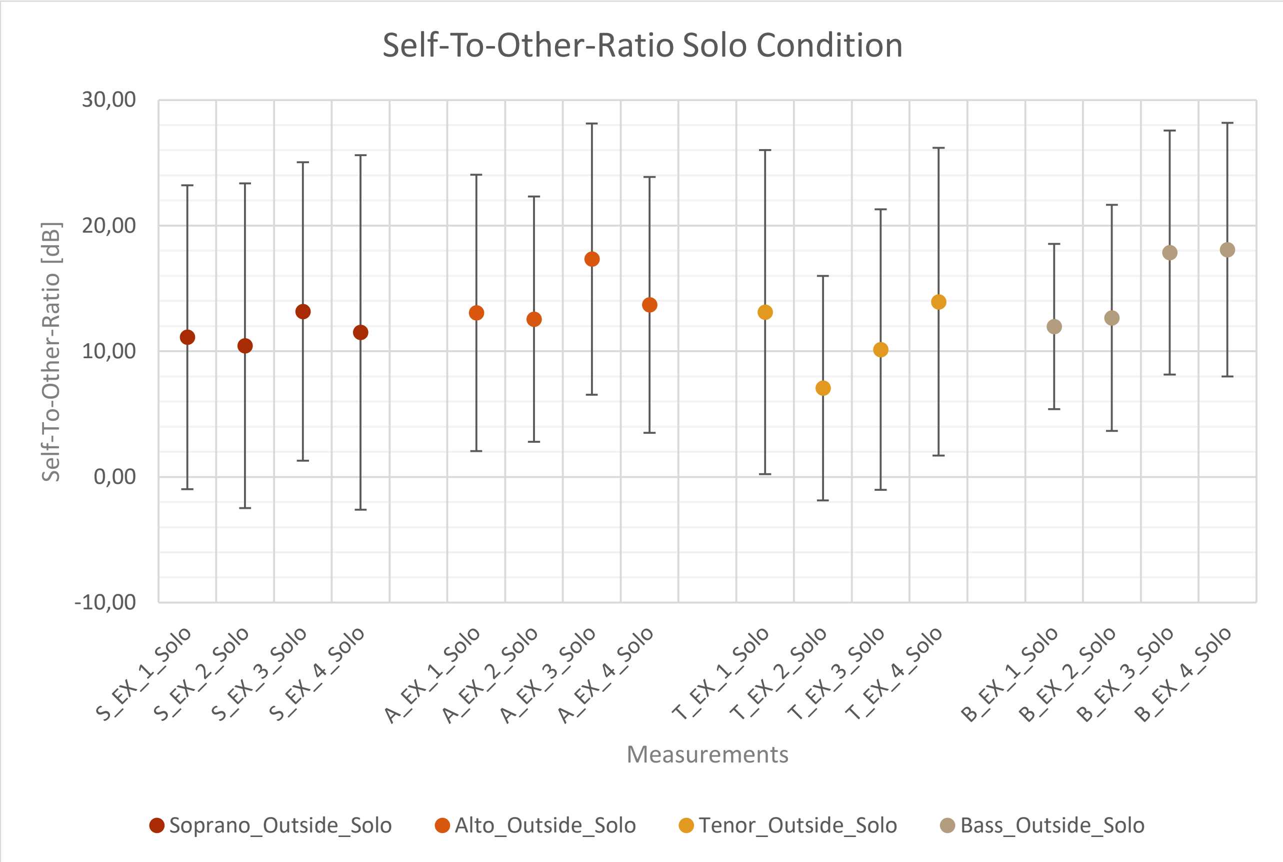


Figure 43 Self-To-Other-Ratio of the four choristers in the "Solo Condition". The lines correspond to the dtandard deviations of the ditributions.

In this case we have the following results: +11.56dB for Soprano (with extremes ranging from +10.44dB to +13.17dB, respectively for the second and third measurements); +14.16dB for Alto (with extremes ranging from +12.54dB to +17.34dB, also in this case for the second and third measurements); +11.06dB for Tenor (with extremes ranging from +7.06dB to +13.93dB, respectively for the second and fourth misurements) and +15.14dB for Bass (with extremes ranging from +11.97dB, in the first measurements, to +18.08dB, in the fourth measurements); for a total average of +12.98dB. The section with the greatest results in all measurements is the Bass.

Also in this case we consider the difference between the values found in the *"Tutti Condition"* and those of the *"Solo Condition"*.

Difference	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+6.02	+6.12	+5.90	+6.27	+6.08
Alto	+9.28	+8.28	+14.41	+9.50	+10.37
Tenore	+10.19	+3.22	+7.99	+8.39	+7.45
Basso	+9.48	+12.05	+14.15	+17.64	+13.33
Avg	+8.74	+7.42	+10.61	+40.45	+9.30

Table 24 Difference between "Solo Condition" and "Tutti Condition" in the various configurations.

The difference in this case is less than 10dB (with extremes ranging from +6.08dB, for Soprano, to +13.33dB, for Bass). Although the Soprano average is the lowest, there is a very small value in the second measurement of Tenor.

6.3.1.3 Relationship between internal and external

The following figures show the graphs comparing the measured SOR in interior and exterior according adopted by the singers. We immediately notice that only for the Soprano there is a SOR greater in the Aula Magna than in the courtyard; for all other sections it is opposite.

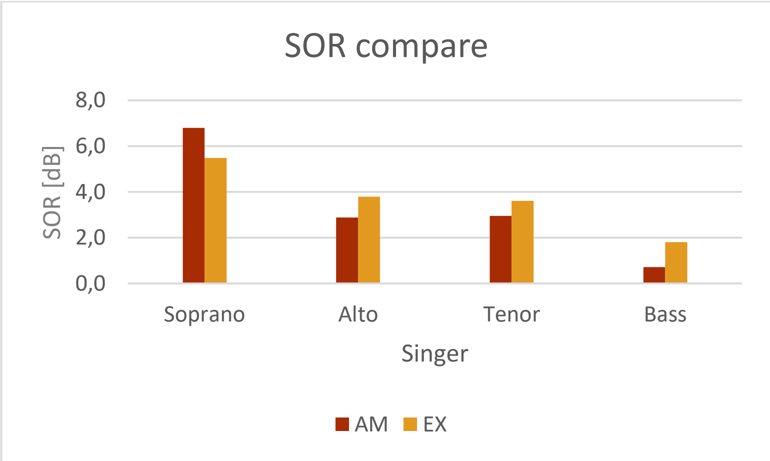


Figura 44 Comparison of the SOR per section based on the measurement location: Aula Magna (AM), courtyard (EX). AM = Aula Magna; EX = Courtyard

In the following figure, instead, we can see in detail the comparison of the single configurations.

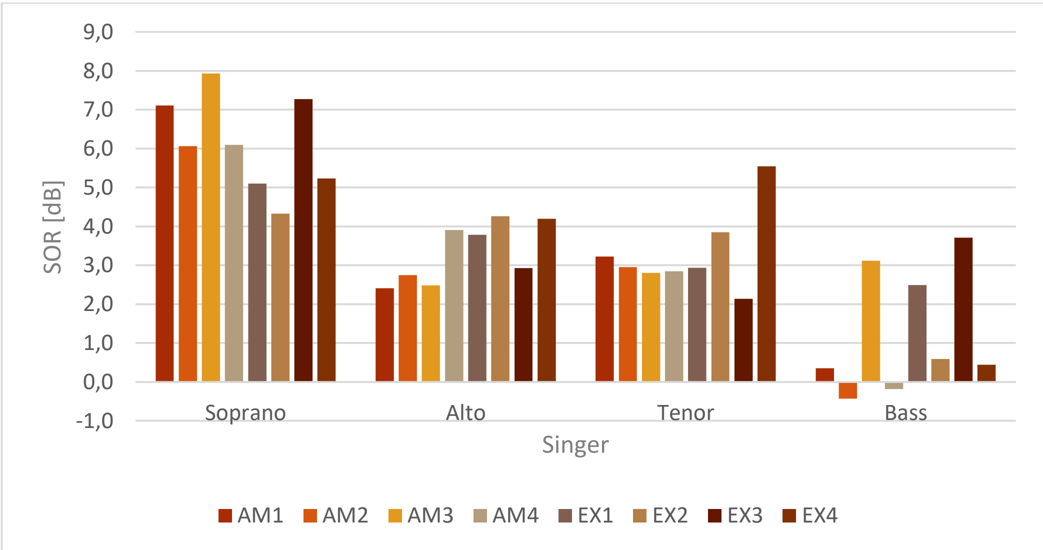


Figure 45 AM1 = First Configuration in Aula Magna; AM2 = Second Configuration in Aula Magna; AM3 = Third Configuration in Aula Magna; AM4 = Fourth Configuration in Aula Magna; EX1 = First Configuration in Courtyard; EX2 = Second Configuration in Courtyard; EX3 = Third Configuration in Courtyard; EX4 = Fourth Configuration in Courtyard.

Soprano

In all measurements the Soprano has a SOR greater than the Aula Magna compared to courtyard. The averages are, respectively, of +6.80dB and +5.48dB.

Soprano	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Aula Magna	+7.11	+6.06	+7.93	+6.10	+6.80
Courtyard	+5.10	+4.33	+7.27	+5.23	+5.48

Table 25 SOR values for the Soprano section in the two environments

In the Aula Magna the position that has found the highest SOR is the third, while the one with the SOR minor is the second.

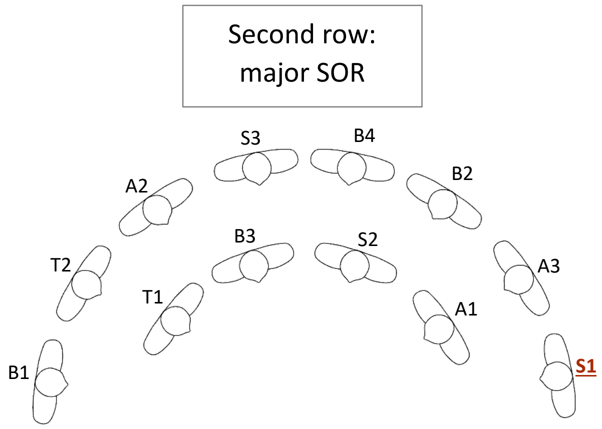


Figure 46 SOR major of the Soprano section in the Aula Magna. Third configuration.

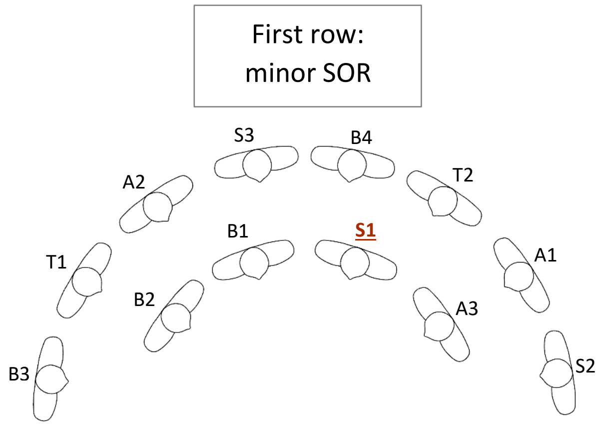


Figure 47 SOR minor of the Soprano section in the Aula Magna. Second configuration.

Considering the exterior, the highest SOR occurs in the third and the minor in the second (as in Aula Magna).

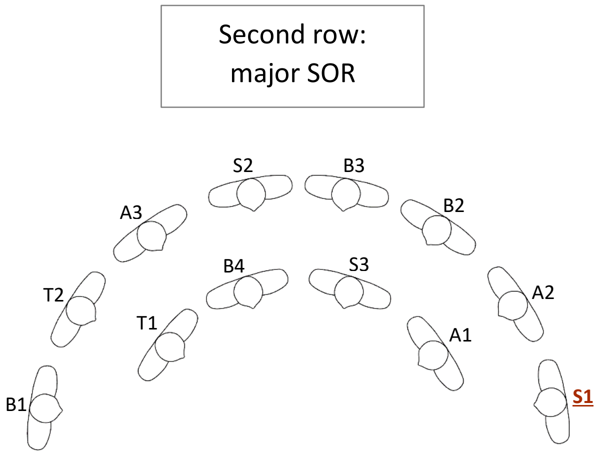


Figure 48 major SOR of the Soprano section in Courtyard. Third Configuration.

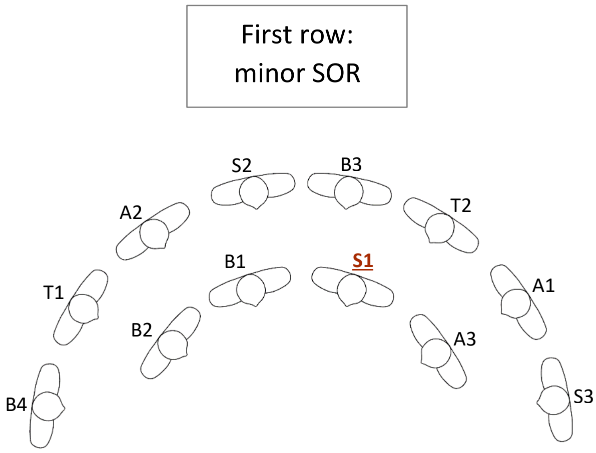


Figure 49 minor SOR of the Soprano section in Courtyard. Second Configuration.

Alto

Alto, unlike the Soprano, found, on average, a higher SOR on the outside, comapred to the Aula Magna.

Alto	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Aula Magna	+2.41	+2.75	+2.49	+3.91	+2.89
Courtyard	+3.78	+4.27	+2.93	+4.20	+3.79

Table 26 SOR values for the Alto section in the two environments

In internal environment we note that the major SOR is in position 4 while the minor in position 1.

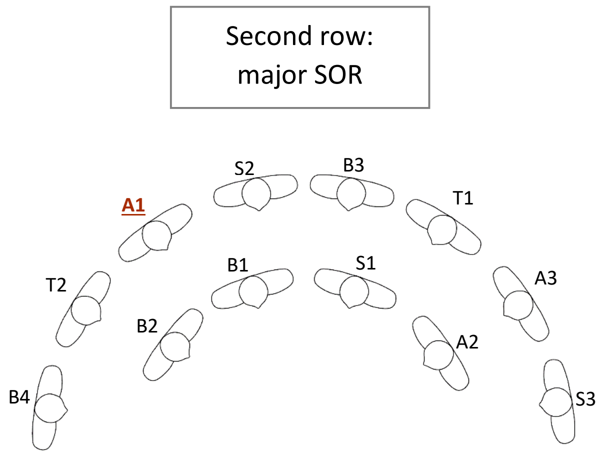


Figure 50 major SOR of the Alto section in the Aula Magna. Four configuration.

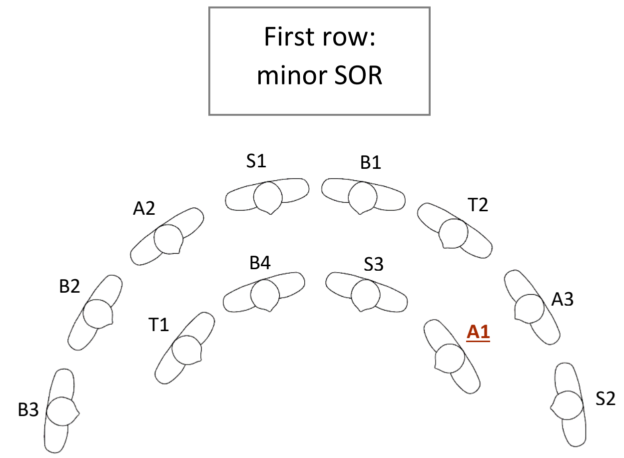


Figura 51 minor SOR of the Alto section in the Aula Magna. First configuration.

Going to consider the exterior, there is a major SOR in the second configuration and a minor SOR in the third configuration.

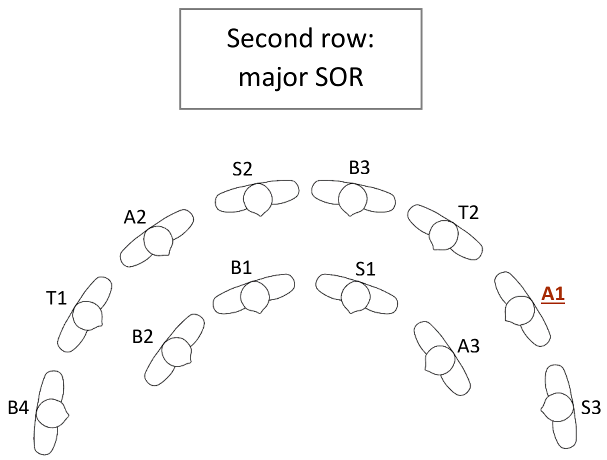


Figure 52 major SOR of the Alto section in the Courtyard. Second configuration.

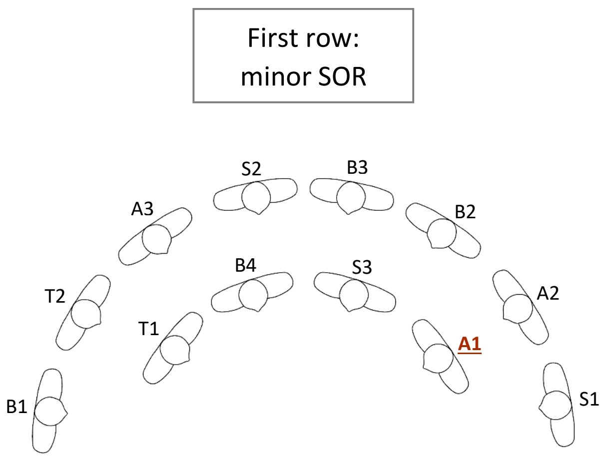


Figure 53 minor SOR of the Alto section in the Courtyard. Third configuration.

We note that, as for the Soprano, we have a major SOR in the second row; this is true both in Aula Magna and courtyard.

Tenor

Also in this case we note that the tenor obtained a higher SOR value in the courtyard than in the Aula Magna.

Tenor	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Aula Magna	+3.22	+2.96	+2.80	+2.85	+2.96
Courtyard	+2.93	+3.85	+2.14	+5.54	+3.62

Table 27 SOR values for the Tenor section in the two environments

In the Aula Magna the position with the highest SOR turns out to be number one; while the one with the minor SOR is the number three.

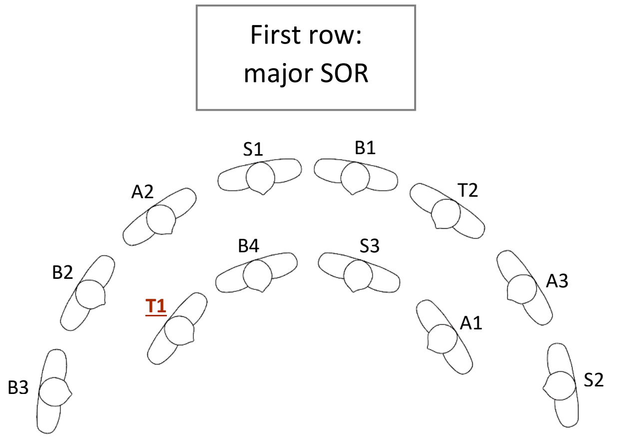


Figure 54 major SOR of the Tenor section in the Aula Magna. First configuration.

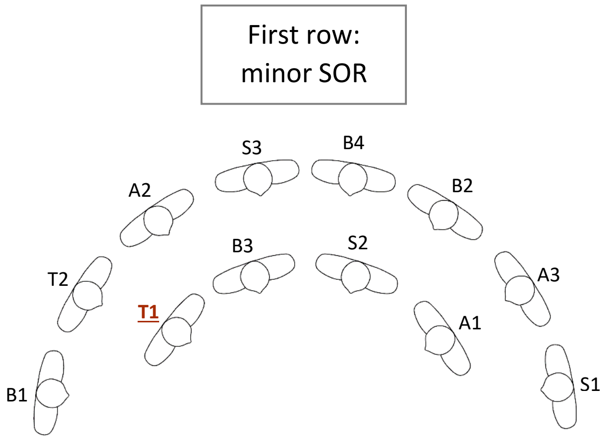


Figure 55 minor SOR of the Tenor section in the Aula Magna. Third configuration.

From figures above we can see that the singer was in the same position. What has changed is the neighbors.

Considering the measurements made in the courtyard, the highest SOR occurs in the fourth measurement while the minor one in the third.

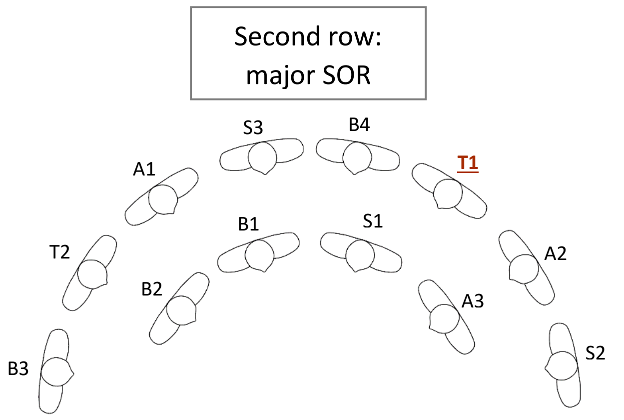


Figure 86 major SOR of the Tenor section in the courtyard. Fourth configuration.

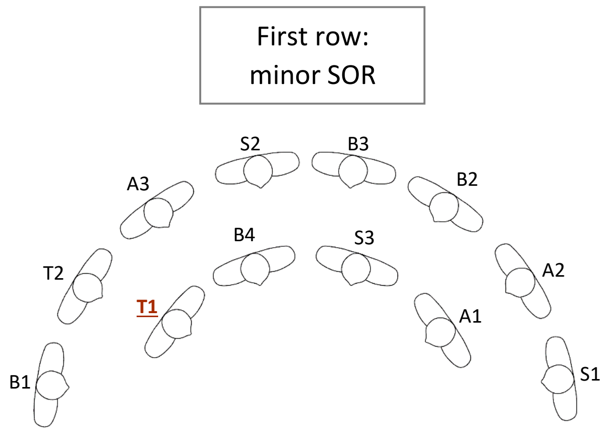


Figure 87 minor SOR of the Tenor section in the courtyard. Third configuration.

We note that the highest SOR is in the second row and the minor one in the first row (as found for Soprano and Alto).

Bass

Even the bass got a major SOR in the courtyard. We note that in this case there are no negative values as for the measurements taken in the Aula Magna.

Bass	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Aula Magna	+0.36	-0.43	+3.11	-0.18	+0.71
Courtyard	+2.49	+0.59	+3.71	+0.44	+1.81

Table 28 SOR values for the Bass section in the two environments

In the Aula Magna there is a major SOR in the third configuration (second row) and a minor SOR in the second (first row).

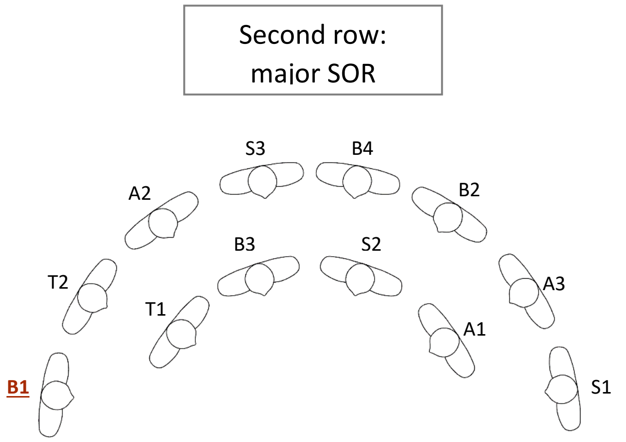


Figure 58 major SOR of the Bass section in the Aula Magna. Third configuration.

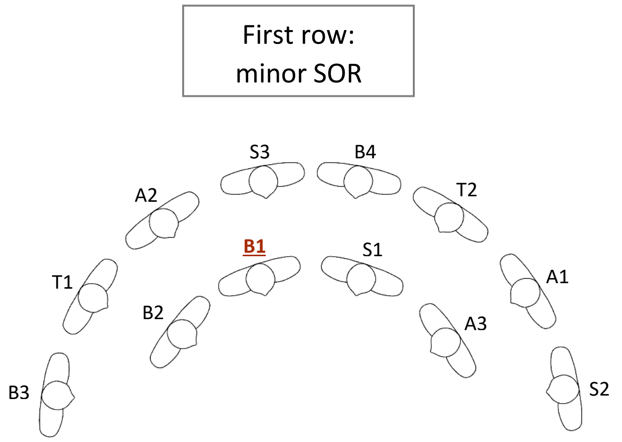


Figure 59 minor SOR of the Bass section in the Aula Magna. Second configuration.

In external, instead, the highest SOR occurs in the third configuration while the minor SOR occurs in the fourth.

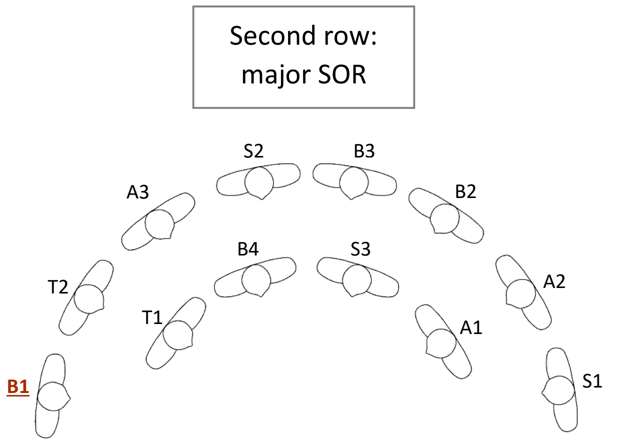


Figure 60 major SOR of the Bass section in the Courtyard. Third configuration.

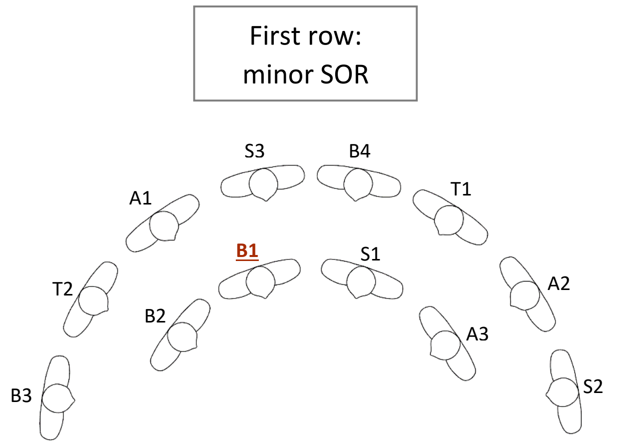


Figure 61 minor SOR of the Bass section in the Courtyard. Fourth configuration.

Also in this case the highest SOR is in the second row while the minor one in the first.

Final Considerations

From the following comparisons it has been noticed that for all four sections there are major SOR values in the second row and minor SOR in the first (with the exception of the tenor in the Aula Magna). Furthermore, except for the Soprano, the SOR value is higher in the Aula Magna than in the courtyard.

6.3.2 Results (Threshold)

In this paragraph the data will be analyzed following the application of the threshold with respect to the histogram of the signal *S*.

6.3.2.1 Aula Magna

As can be seen from the table and graph below, the total average of the SOR in Aula Magna is +3.89dB (with extremes ranging from -0.90dB to +9.77dB).

SOR	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Avg
Soprano	+7.92	+7.91	+9.77	+7.30	+8.23
Alto	+2.47	+2.98	+2.70	+4.09	+3.06
Tenor	+3.84	+4.02	+3.19	+3.84	+3.72
Bass	+0.31	-0.90	3.18	-0.29	+0.57
Avg	+3.63	+3.50	+4.71	+3.73	+3.89

Table 29 SOR values per section found in the four configurations carried out in the Aula Magna; "Tutti Condition". This is the result with the application of the threshold

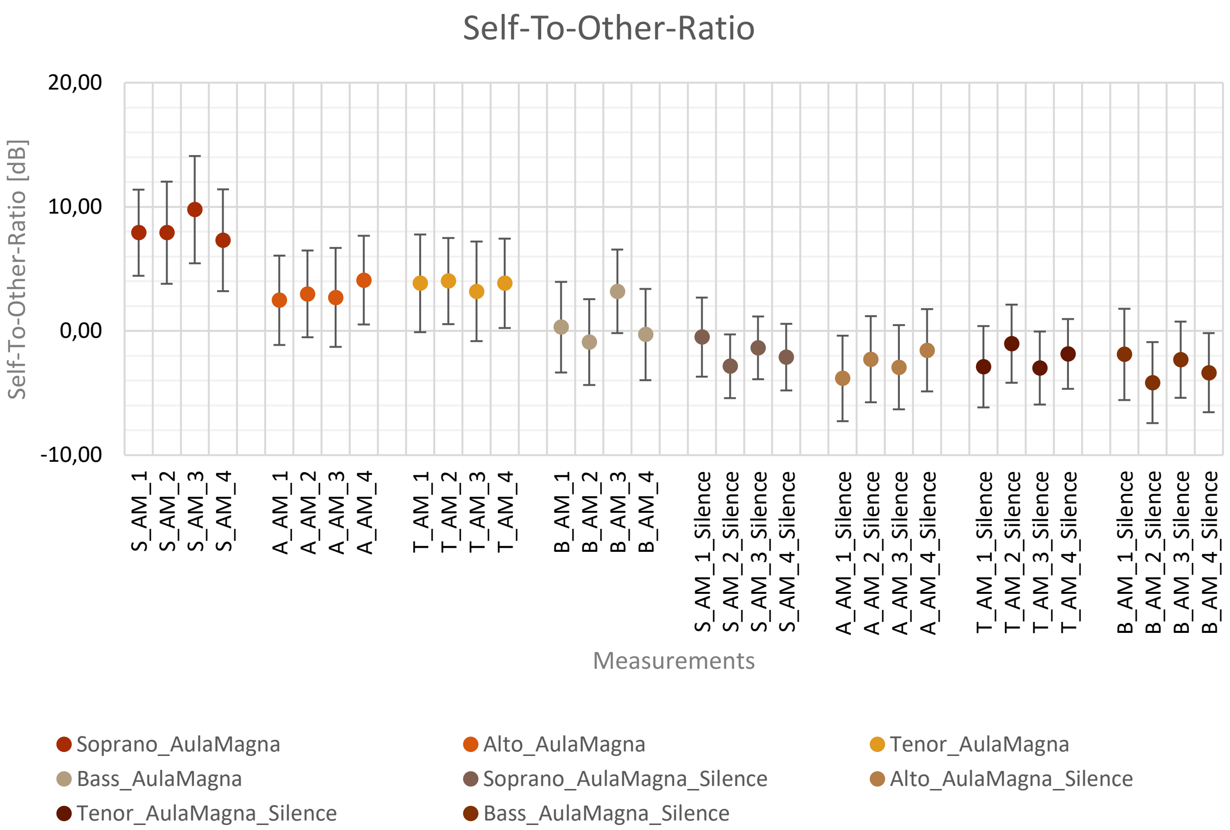


Figure 62 Self-To-Other-Ratio of the four configurations per subject. The first four series refer to the values of the "Tutti Condition", while the last four refer to the "Silence Condition". The bars indicate the standard deviations of the distributions.

Considering the value of the SOR in the *"Tutti Condition"*, on average, we have the following results: Soprano +8.23dB, with extremes ranging from +7.30dB (in the fourth configuration) to +9.77dB (in the third configuration); Alto +3.06dB with extremes ranging from +2.47dB (in the first configuration) to +4.09dB (in the fourth configuration); Tenor +3.72dB with extremes ranging from +3.19dB (in the third configuration) to +4.02dB (in the second measurement); Bass +0.57dB with extremes ranging from -0.90dB (in the second configuration) to +3.18dB (in the third configuration). Also in this case the Soprano has higher SOR value than the other sections and the Bass has two value of SOR tless than zero (as in the case without threshold there are in the second and fourth configuration, respectively –0.90dB and -0.29dB).

Going to consider the standard deviations on average we have the following values: Soprano +4.01; Alto +3.66; Tenor +3.75; Bass+3.54. Soprano is the one with the highest standard deviation. On average the standard deviations is +3.74. The following table summarizes the values of this parameter for the various measurements; we immediately note that they are significantly smaller than in the case withour applying the threshold.

Dv.Std_Tutti	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+3.47	+4.11	+4.33	+4.11	+4.01
Alto	+3.59	+3.50	+3.99	+3.58	+3.66
Tenor	+3.94	+3.47	+4.00	+3.60	+3.75
Bass	+3.65	+3.47	+3.37	+3.67	+3.74

Table 30 Standard deviations of the four configurations carried out in the Aula Magna based on the four sections ("Tutti Condition")

Also in this case, in the previous figure (56), the last four series refer to the *"Silence Condition"*, in which there is a total average of -2.37dB. The following table shows the values in detail.

Silence	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	-0.50	-2.85	-1.36	-2.12	-1.71
Alto	-3.83	-2.29	-2.93	-1.57	-2.65
Tenor	-2.89	-1.03	-2.99	-1.85	-2.19
Bass	-1.89	-4.18	-2.32	-3.37	-2.94
Avg	-2.28	-2.59	-2.40	-2.23	-2.37

Table 31 Values of the various configurations, in Aula Magna, for the "Silence Condition".

Analyzing the data, we have the following results (on average): Soprano -1.71dB (with extremes ranging from -2.85dB, in the second configuration, to -0.5dB in the first configuration); Alto -2.65dB (with extremes ranging from -3.83dB in the first configuration to -1.57dB in the fourth configuration); Tenor -2.19dB (with extremes ranging from -2.99dB to -1.03dB, respectively in the second and in the first configuration) and Bass -2.94 (with extremes ranging from -4.18, in the second configuration, to 1.89, in the first configuration). In this case, consideting the standard deviations, there is a margin of error of +3.12.

The table below shows the analysis of the *"Solo Condition"*, therefore of the SOR with respect to the reverberation of the room. On average we have a value of +16.96db with extremes ranging from +12.55dB, in the first Soprano configuration, to +20.09dB in the third bass configuration.

Solo	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+12.55	+14.02	+15.92	+14.22	+14.18
Alto	+18.50	+15.99	+19.16	+16.14	+17.45
Tenor	+19.48	+15.80	+19.38	+16.92	+17.89
Bass	+16.63	+19.41	+20.09	+17.12	+18.31
Avg	+16.79	+16.31	+18.64	+16.10	+16.96

Table 32 Values of the various configurations, in Aula Magna, for the "Solo Condition".

Analyzing the data by section the following results are found: Soprano +14.18dB (with extremes ranging from +12.55dB, in the first configuration, to +15.92dB, in the third configuation); Alto +17.45dB (with extremes ranging from +15.99dB to +19.16dB, respectively in the second and third configurations); Tenor +17.89dB (with extremes ranging from +15.80dB to +19.48dB, respectively in the second and in the first configuration); Bass +18.31dB (with extremes ranging from +16.63dB to +20.09dB, respectively in the first and third configuration). These results, with the relative standard deviations, are also shown in the graph below.

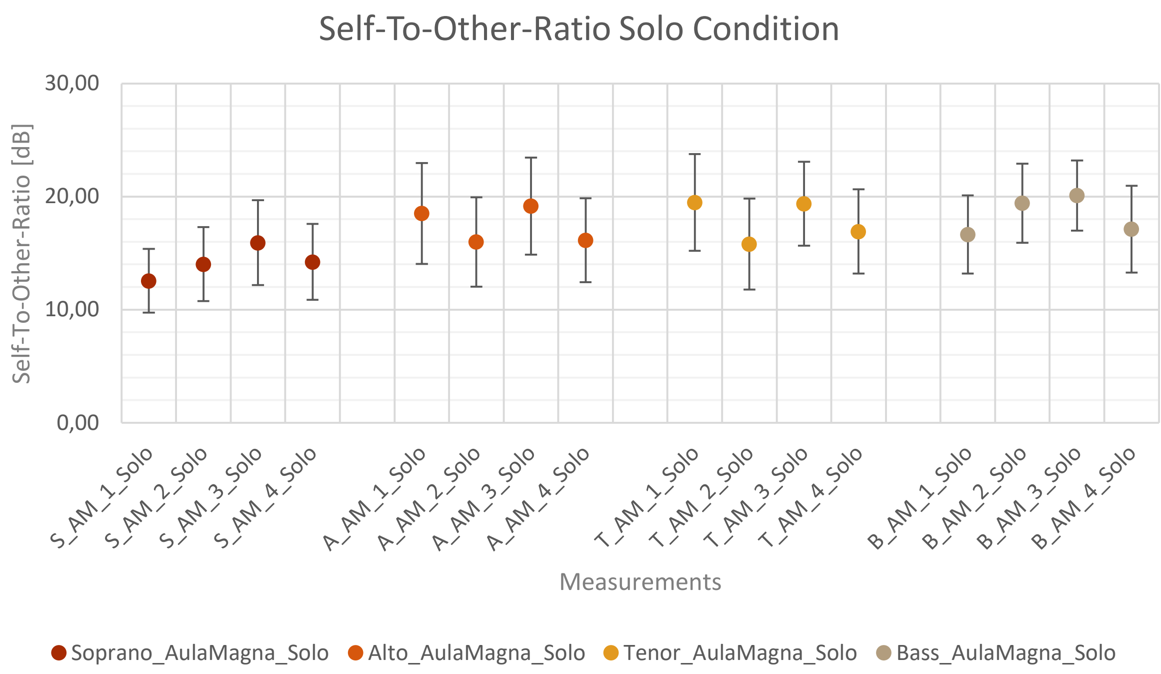


Figure 63 Self-To-Other-Ratio of the Aula Magna measurements of the "Solo Condition" with relative standard deviations.

Also in this case, to derive the relationshop between the sound of the choir and the diffuse field of the reflections of one's voice in the room, the difference between the *"Solo Condition"* and *"Tutti Condition"* are analyzed.

Difference	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+4.63	+6.11	+6.15	+6.92	+5.95
Alto	+16.04	+13.01	+16.46	+12.06	+14.39
Tenor	+15.64	+11.78	+16.19	+13.08	+14.17
Bass	+16.33	+20.31	+16.91	+17.41	+17.74
Avg	+13.16	+12.80	+13.93	+12.36	+13.06

Table 33 Difference between "Solo Condition" and "Tutti Condition" in the various configurations. Relationship between the diffuse field of room reflections and the sound of the choir.

On average there is a total difference of +13.06dB (with extremes ranging from +5.95dB, for the Soprano, to +17.74dB for the Bass). It can therefore be said that the diffuse field of reflections in the room of one's voice is 13dB weaker than the sound of other choristers. The choir masks the reflections of the singer's voice. Also in this case the lower values are given by the Soprano and the greater by the Bass.

6.3.2.2 Internal courtyard of the Polytechnic, Corso Duca degli Abruzzi side

Also in this case, the table below and the graph summarize the SOR data relating to the various configurations taken in the external environment. On average there is a SOR of +4.09dB (with extremes ranging from +0.27dB, in the second configuration of the Bass, to +8.52dB, in the third configuration of Soprano).

SOR	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+6.87	+5.75	+8.52	+5.97	+6.78
Alto	+3.93	+4.50	+2.95	+4.40	+3.94
Tenor	+3.27	+3.97	+2.65	+6.26	+4.04
Bass	+2.01	+0.27	+3.71	+0.32	+1.60
Avg	+4.02	+3.62	+4.46	+4.45	+4.09

Table 34 SOR values per section found in the four configurations carried out in the courtyard; "Tutti Condition". This is the result with the application of the threshold

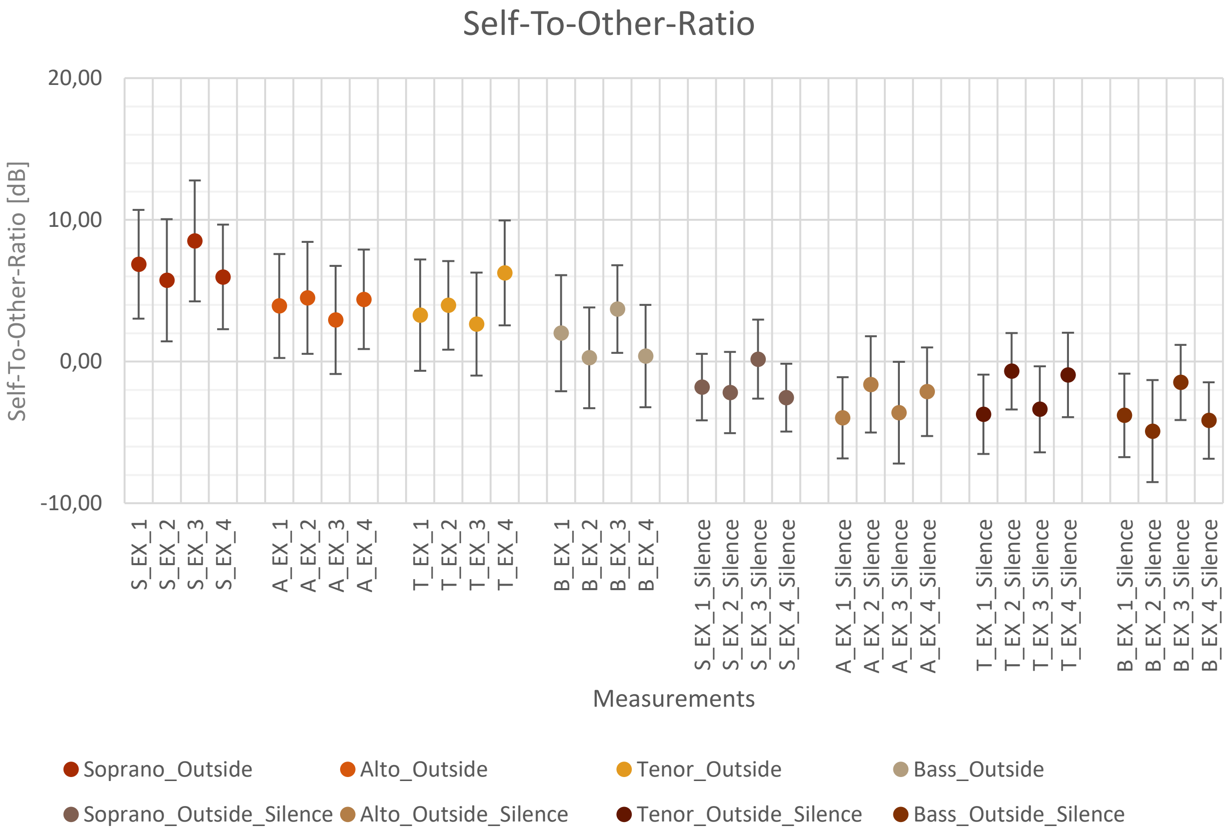


Figure 64 Self-To-Other-Ratio of the four configurations per subject. The first four series refer to the values of the "Tutti Condition", while the last four refer to the "Silence Condition". In both cases the threshold was applied to the results. The bars indicate the standard deviations of the distributions.

The following SOR values can be seen from the graph: Soprano +6.78dB with extremes ranging from +5.75dB (in the second configuration) to +8.52dB (in the third configuration); Alto +3.94dB with extremes ranging from +2.95 dB (in the third configuration) to +4.50dB (in the second configuration); Tenor +4.04dB with extremes ranging from +2.65dB (in the third configuration) to +6.26dB (in the fourth configuration); Bass +1.60dB with extremes ranging from +0.27dB (in the second configuration) to +3.71dB ((in the third configuration). The highest SOR is found in the Soprano while the minor in the Bass.

The standard deviations on average are the following: Soprano +4.03dB; Alto +3.73dB; Tenor +3.60dB; Bass +3.59dB; for a total average of +3.74dB. Also in this case we have higher values for the Soprano section.

Dv.Std_Tutti	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+3.84	+4.31	+4.26	+3.69	+4.03
Alto	+3.67	+3.94	+3.81	+3.51	+3.73
Tenor	+3.92	+3.13	+3.64	+3.70	+3.60
Bass	+4.10	+3.56	+3.10	+3.61	+3.59

Table 35 Standard deviations of the four configurations carried out in the Courtyard based on the four sections ("Tutti Condition").

Analyzing the *"Silence Condition"* we have an average of -2.54. As can be seen also from the table below in the third Soprano measurement we have a value greater than zero: +0.18.

Silence	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	-1.81	-2.18	**+0.18**	-2.55	-1.59
Alto	-3.97	-1.61	-3.61	-2.12	-2.83
Tenor	-3.72	-0.68	-3.63	-0.93	-2.17
Bass	-3.80	-4.90	-1.47	-4.15	-3.58
Avg	-3.23	-2.34	-2.07	-2.44	-2.54

Table 36 Values of the various configurations, in Courtyard, for the "Silence Condition".

Analyzing the data, we have the following results (on average): Soprano -1.59dB (with extremes ranging from -2.55dB, in the fourth configuration, to +0.18dB in the third configuration); Alto -2.83dB (with extremes ranging from -3.97dB in the first configuration to -1.61dB in the second configuration); Tenor -2.17dB (with extremes ranging from -3.72dB to -0.68dB, respectively in the first and in the second configuration); Bass -3.58dB (with extremes ranging from. -4.90dB to -1.47dB, respectively in the second configuration and in the third configuration). In this case, considering the standard deviations, there is a margin of error of +3.12.

The following table and the figure below show the values of the "*Solo Condition"*.

Solo	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Soprano	+12.31	+11.68	+14.51	+12.32	+12.71
Alto	+14.67	+14.07	+19.12	+15.80	+15.92
Tenor	+14.75	+7.75	+11.26	+15.35	+12.28
Bass	+12.07	+13.26	+18.83	+19.16	+15.83
Avg	+13.45	+11.69	+15.93	+15.66	+14.18

Table 37 Values of the various configurations, in Courtyard, for the "Solo Condition".

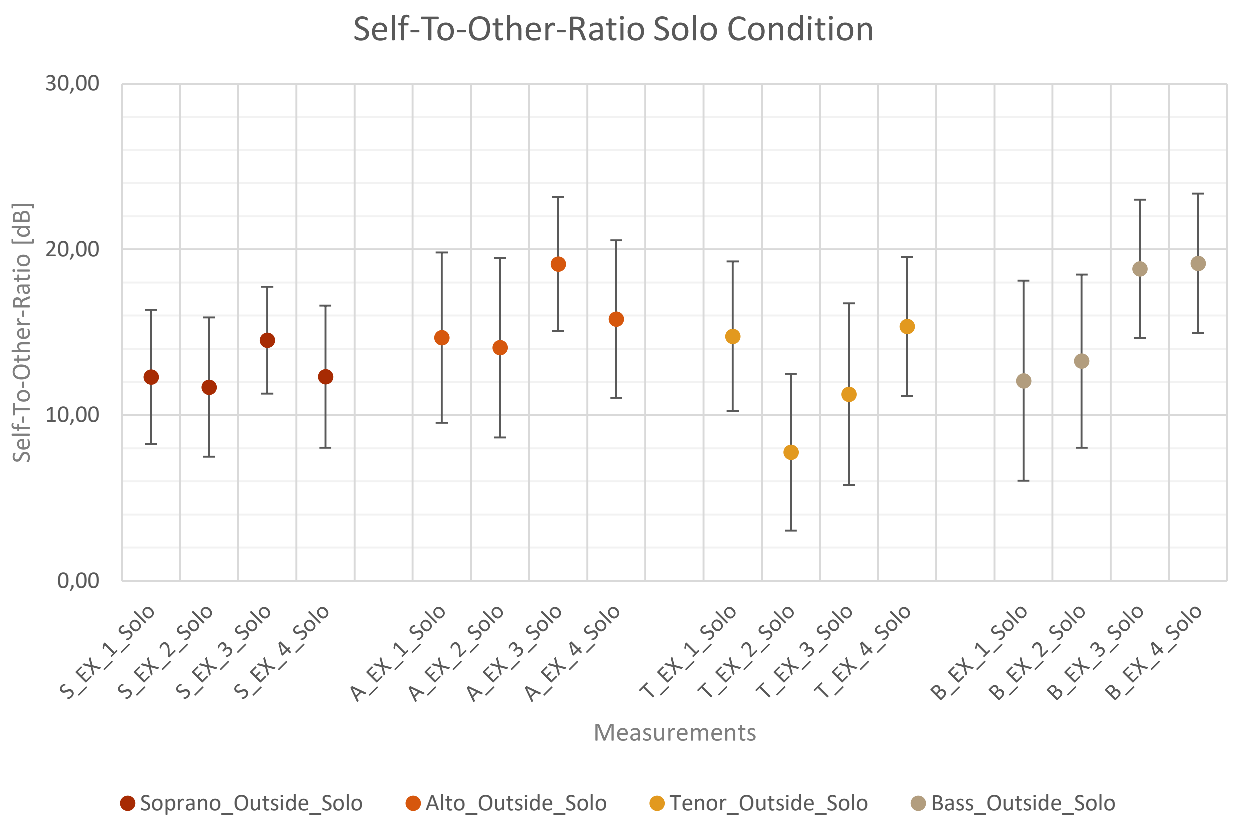


Figure 65 Self-To-Other-Ratio of the Courtyard measurements of the "Solo Condition" with relative standard deviations.

In detail we have the following results: Soprano +12.71dB (with extremes ranging from +11.68dB to +14.51dB, respectively in the second and third configuration); Alto +15.92 (with extremes ranging from +14.07dB to +19.12dB, also in this case in the second and third configuration); Tenor +12.28dB (with extremes ranging from +7.75dB, in the second configuration, to +15.35dB, in the fourth configuration); Bass +15.83dB (with extremes ranging from +12.07dB to +19.16dB, respectively in the first and in the fourth configuration). The total average is +14.18dB. Considereing the differences between the *"Solo Condition"* and the *"Tutti Condition"* we see an increase of 10dB. The results regarding this difference are summarized in the table below.

Difference	**Configuration 1**	**Configuration 2**	**Configuration**	**Configuration 4**	*Avg*
Soprano	+5.43	+5.93	+5.99	+6.35	+5.93
Alto	+10.74	+9.57	+16.18	+11.40	+11.98
Tenor	+11.47	+3.78	+8.61	+9.09	+8.24
Bass	+10.06	+12.99	+15.12	+18.77	+14.23
Avg	+9.43	+8.07	+11.48	+11.40	+10.09

Table 38 Difference between "Solo Condition" and "Tutti Condition" in the various configurations.

6.3.2.3 Relationship between internal and external

The following figures show the graphs comparing the measured SOR in Aula Magna (AM) and in Courtyard (EX). We immediately notice that only for the Soprano there is a SOR greater in the Aula Magna than in the courtyard; for all other sections it is opposite.

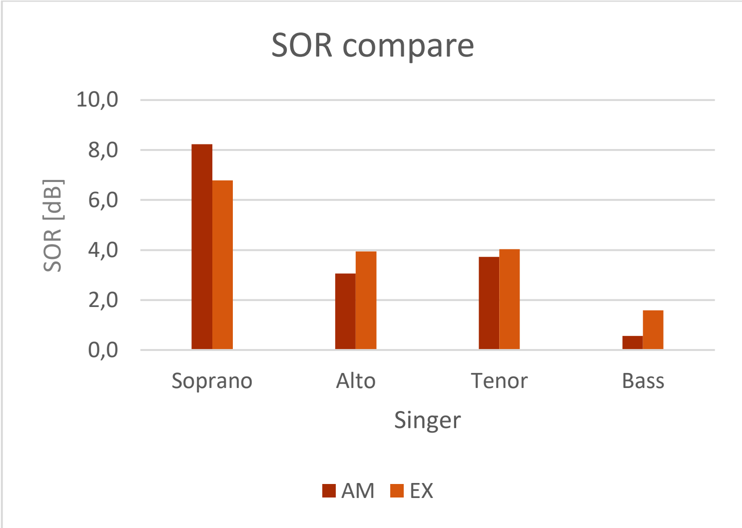


*Figure 66 Comparison of the SOR per section based on the measurement location: Aula Magna (AM), courtyard (EX**).***

In the following figure, instead, we can see in detail the comparison of the single configurations.

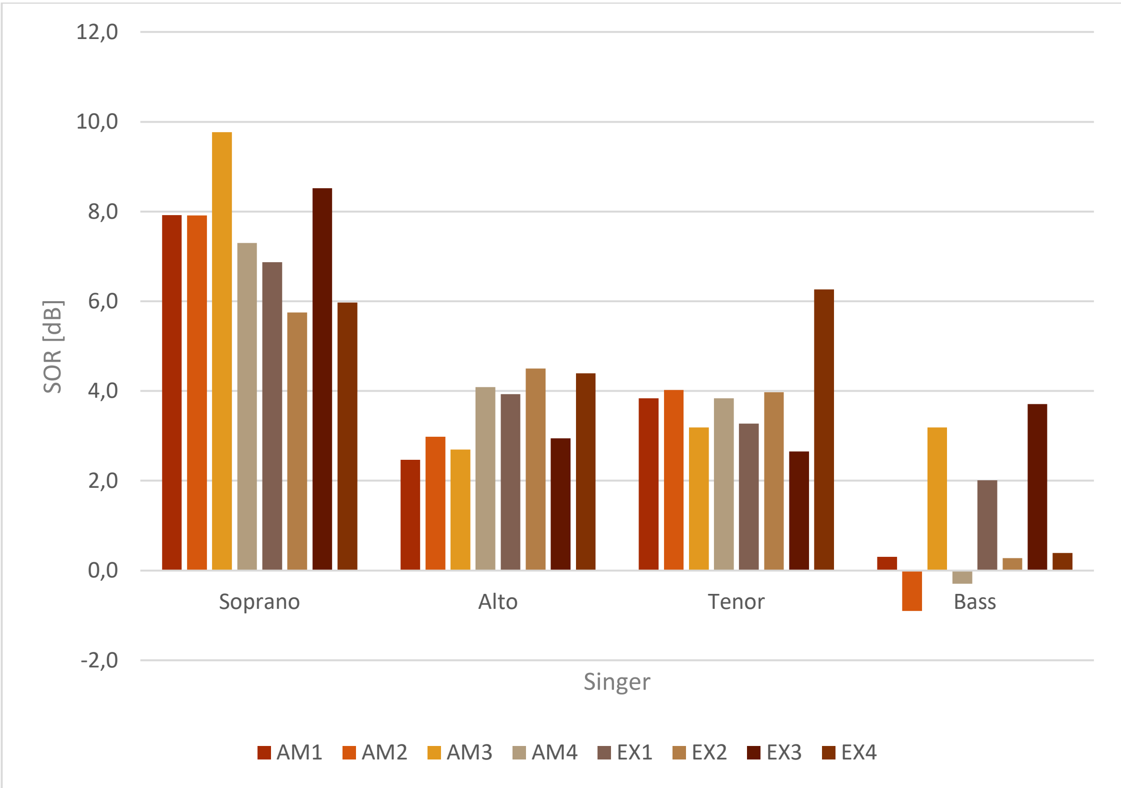


Figure 67 AM1 = First Configuration in Aula Magna; AM2 = Second Configuration in Aula Magna; AM3 = Third Configuration in Aula Magna; AM4 = Fourth Configuration in Aula Magna; EX1 = First Configuration in Courtyard; EX2 = Second Configuration in Courtyard; EX3 = Third Configuration in Courtyard; EX4 = Fourth Configuration in Courtyard.

Soprano

In all measurements the Soprano has a SOR greater than the Aula Magna compared to courtyard. The averages are, respectively, of +8.23dB and +6.78dB.

Soprano	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Aula Magna	+7.92	+7.91	+9.77	+7.30	+8.23
Courtyard	+6.87	+5.75	+8.52	+5.97	+6.78

Table 39 SOR values for the Soprano section in the two environments

In the Aula Magna the position that has found the highest SOR is the third, while the one with the SOR minor is the fourth.

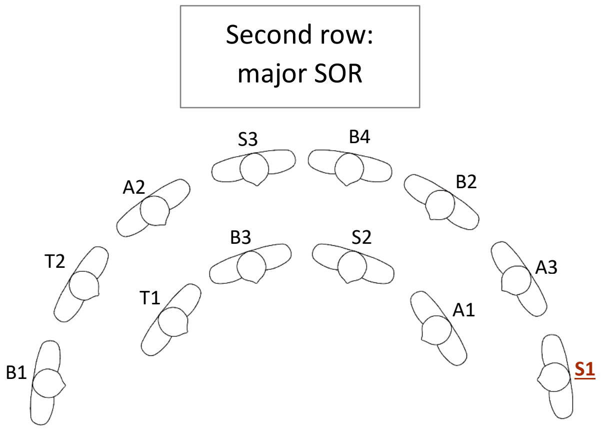


Figure 68 SOR major of the Soprano section in the Aula Magna. Third configuration.

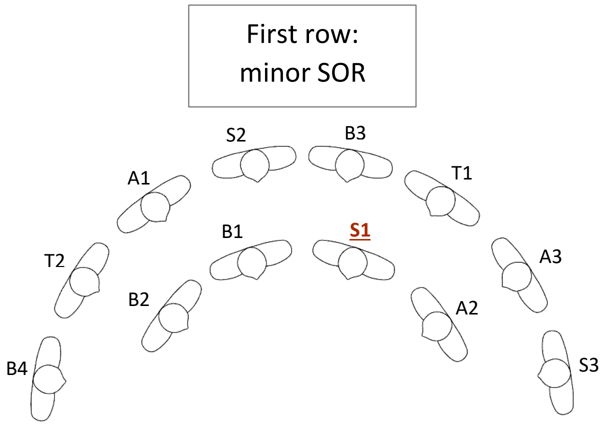


Figure 69 SOR minor of the Soprano section in the Aula Magna. Fourth configuration.

Considering the exterior, the highest SOR occurs in the third and the minor in the second (as in Aula Magna).

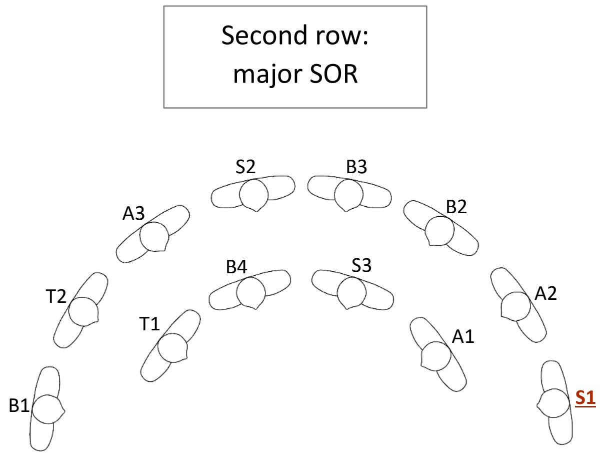


Figure 70 major SOR of the Soprano section in Courtyard. Third Configuration.

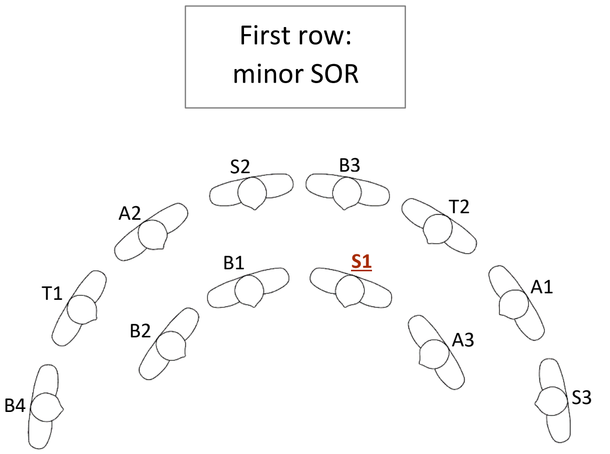


Figure 71 minor SOR of the Soprano section in Courtyard. Second Configuration.

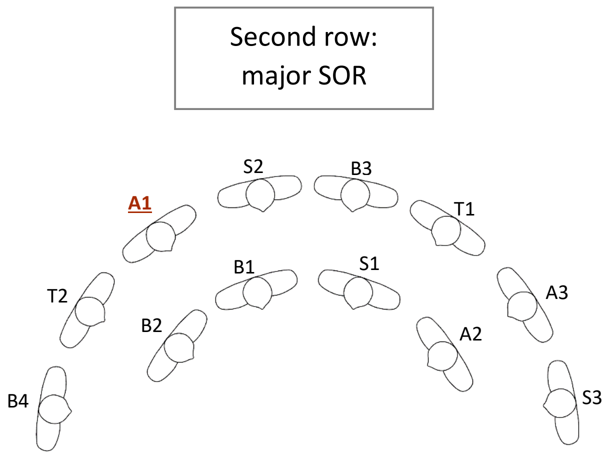
Alto

Alto, unlike the Soprano, found, on average, a higher SOR on the outside, comapred to the Aula Magna.

Alto	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Aula Magna	+2.47	+2.98	+2.70	+4.09	+3.06
Courtyard	+3.93	+4.50	+2.95	+4.40	+3.94

Table 40 SOR values for the Alto section in the two environments

In internal environment we note that the major SOR is in position 4 while the minor in position 1.



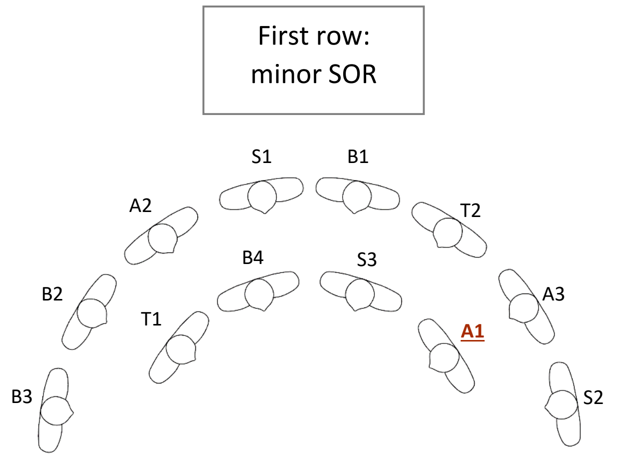
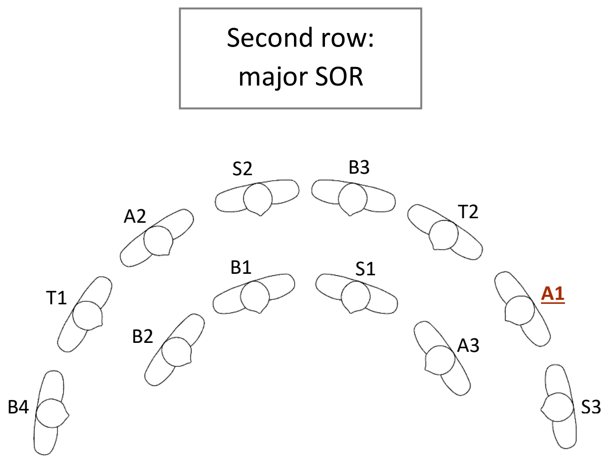


Figure 72 major SOR of the Alto section in the Aula Magna. First configuration.

Figura 73 minor SOR of the Alto section in the Aula Magna. Second configuration.

Going to consider the exterior, there is a major SOR in the second configuration and a minor SOR in the third configuration.



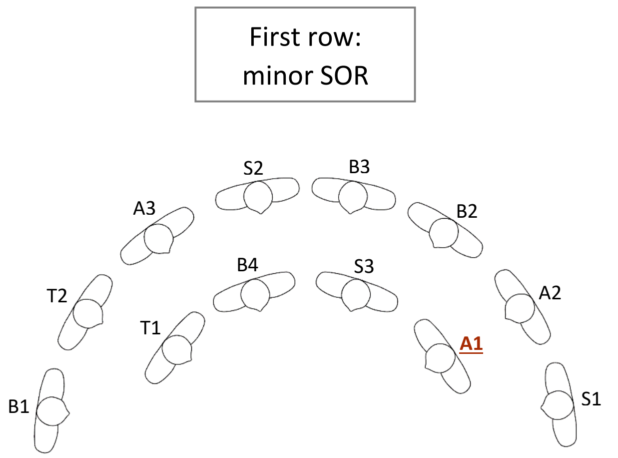


Figure 74 major SOR of the Alto section in the Courtyard. Second configuration.

Figure 75 minor SOR of the Alto section in the Courtyard. Third configuration.

We note that, as for the Soprano, we have a major SOR in the second row; this is true both in Aula Magna and courtyard.

Tenor

Also in this case we note that the tenor obtained a higher SOR value in the courtyard than in the Aula Magna.

Tenor	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Aula Magna	+3.84	+4.02	+3.19	+3.84	+3.72
Courtyard	+3.27	+3.97	+2.65	+6.26	+4.04

Table 41 SOR values for the Tenor section in the two environments

In the Aula Magna the position with the highest SOR turns out to be number two; while the one with the minor SOR is the number three.

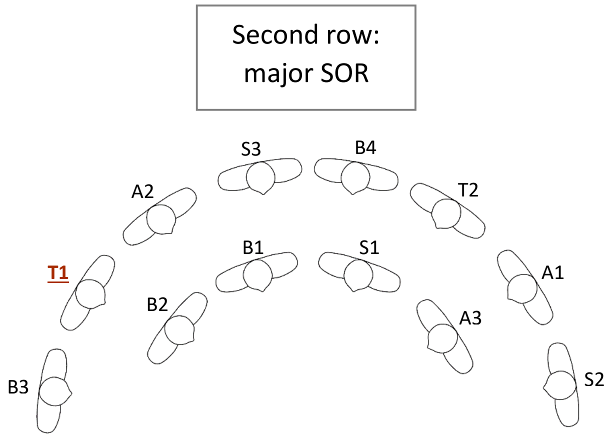


Figure 76 major SOR of the Tenor section in the Aula Magna. Second configuration.

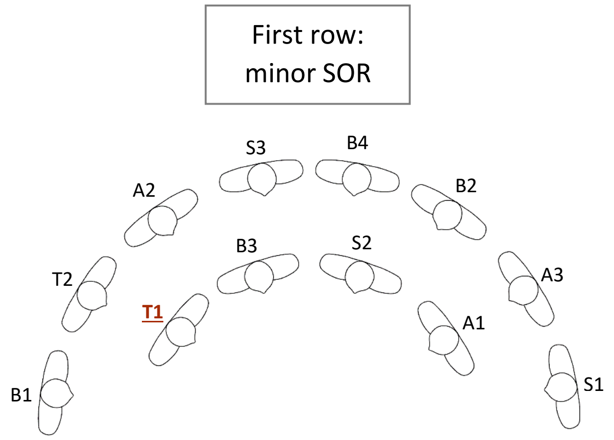


Figure 77 minor SOR of the Tenor section in the Aula Magna. Third configuration.

Unlike the data without the application of the threshold, we note that even in this case the highest SOR occurs in the back row.

Considering the measurements made in the courtyard, the highest SOR occurs in the fourth measurement while the minor one in the third.

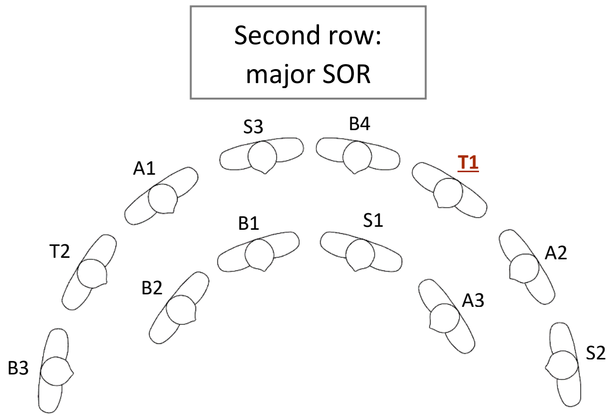


Figure 78 major SOR of the Tenor section in the courtyard. Fourth configuration.

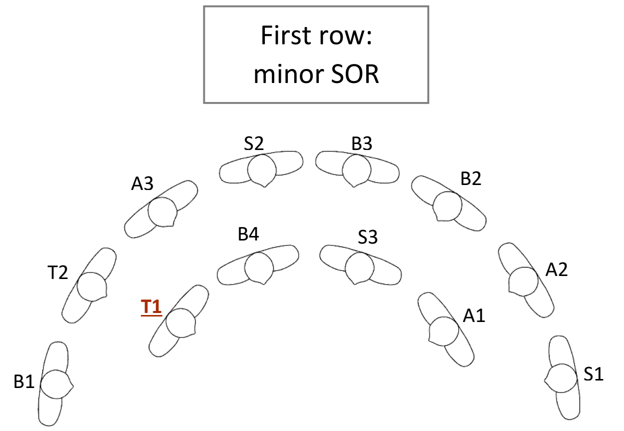


Figure 79 minor SOR of the Tenor section in the courtyard. Third configuration.

Bass

Even the bass got a major SOR in the courtyard.

Bass	**Configuration 1**	**Configuration 2**	**Configuration 3**	**Configuration 4**	*Avg*
Aula Magna	+0.31	-0.90	+3.18	-0.29	+0.57
Courtyard	+2.01	+0.27	+3.71	+0.39	+1.60

Table 42 SOR values for the Bass section in the two environments

In the Aula Magna there is a major SOR in the third configuration (second row) and a minor SOR in the second (first row, negative value).

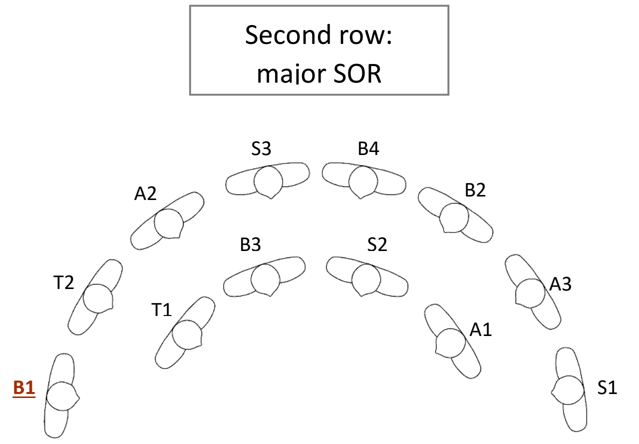


Figure 80 major SOR of the Bass section in the Aula Magna. Third configuration.

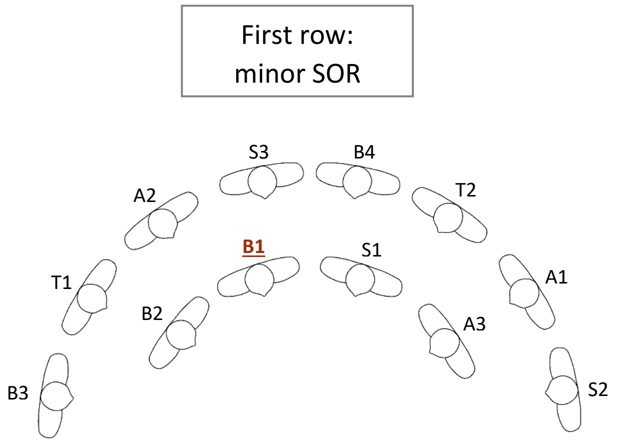


Figure 81 minor SOR of the Bass section in the Aula Magna. Second configuration.

In external, instead, the highest SOR occurs in the third configuration while the minor SOR occurs in the second.

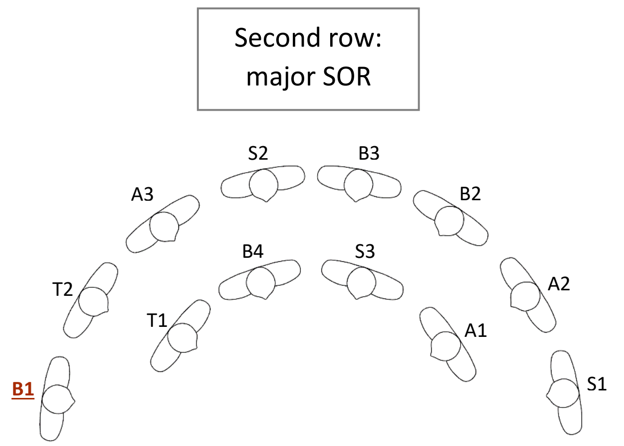


Figure 82 major SOR of the Bass section in the Courtyard. Third configuration.

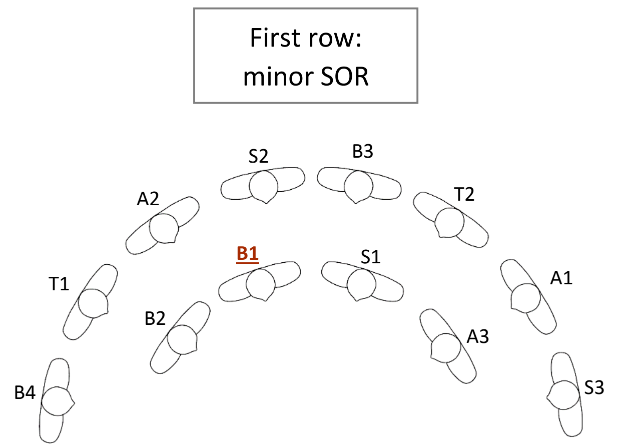


Figure 83 minor SOR of the Bass section in the Courtyard. Fourth configuration.

Also in this case the highest SOR is in the second row while the minor one in the first.

Final Considerations

From the following comparisons it has been noticed that for all four sections there are major SOR values in the second row and minor SOR in the first (also for Tenor). Furthermore, except for the Soprano, the SOR value is higher in the Aula Magna than in the courtyard.

6.3.3 Comparison of data with and without the threshold

Considering the values found by applying or not the threshold, we can summarize the data in the following table

SOR_Tot	**No_Threshold_AM**	**Threshold _AM**	**No_ Threshold _EX**	**Threshold _EX**
Soprano	+6.80	+8.23	+5.48	+6.78
Alto	+2.89	+3.06	+3.79	+3.94
Tenor	+2.96	+3.72	+3.62	+4.04
Bass	+0.71	+0.57	+1.81	+1.60
Avg	+3.34	+3.89	+3.68	+4.09

Table 43 Comparative table between application and not of the threshold, both for the Aula Magna (AM) and Courtyard (EX).

We note that for all sections, except for the Bass, with the application of the threshold, greater results are obtained.

For the optimization of the acoustic shell it was decided to take into consideration the results with the threshold.

6.3.4 Measured SOR and calculated SOR

Considering the formulas reported in chapter 3.3 *"Calculation of the SOR parameter"* we can obtain the SOR value taking into account the acoustic of the Aula Magna.

1. Area of equivalent absorption and average absorption of the room
   The *Reverberation Time* in Aula Magna is the following

	62.5	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Tr [s]	1.41	1.41	1.34	1.21	1.21	1.07	1	0.97

Table 44 Reverberation time calculated in Aula Magna

   From *Sabine's formula* we get the equivalent absorption area *A* (Volume of the Aula Magna is 3640 m^3).

	62.5	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
A $[m^2]$	415.63	415.63	437.34	484.33	484.33	547.70	586.04	604.16

   Considering a total surface of 2027 m^2, the absorption coefficients are obtained

	62.5	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
α	0.19	0.19	0.19	0.21	0.21	0.24	0.25	0.26

2. During the measurements, with a sound level meter, the SPL was also measured in the position of the conductor: this correponds to +75.4dB. Now, we can calculate the intensity at one poitn in the diffuse field

$$I = 10^{7.54} \times 10^{-12} = 0.00003 \left[\frac{W}{m^2}\right]$$

3. Average power per singer

	62.5	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
W	0.0036	0.0036	0.0038	0.0042	0.0042	0.0048	0.0051	0.0053
W_i	0.00030	0.00030	0.00032	0.00035	0.00035	0.00040	0.00043	0.00044

   To calculate W_i I divide the power **W** by the total number of singers, or twelve.

4. SIL of Other
   In this case the average distance between the neighbors is 0.55m and since the formation is divided in two lines, the number of neighbors is approximated to five.

	62.5	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
I	0.0004	0.0004	0.00045	0.0005	0.0005	0.00055	0.0006	0.0006

SIL_{Other}	86.3	86.3	86.5	86.9	86.9	87.4	87.7	87.8

5. SIL of Self

   Considering the power per singer calculated in point three anda a mouth-eat distance of 15cm we have the following values of the intensity and *SIL*

	62.5	125	250	500	1000	2000	4000	8000
I	0.00043	0.00043	0.00045	0.0005	0.0005	0.00055	0.0006	0.0006
SIL_{Self}	90.3	90.3	90.5	91.0	91.0	91.5	91.8	91.9

6. SOR

$$SOR = SIL_{Self} - SIL_{Other} = 100.1 - 96.1 = 4.1dB$$

The value of the calculated SOR is close enough to that measured and analyzed with the application of the threshold equal to +3.89dB.

6.3.5 Questionnaires

The questionnaire was divided into theree parts: the first is the general part with questions about the subject (for example age, section or questions like “Have you ever taken singing lessons?” or “Did you sing in other choirs?”); the second concerning the individual configurations and the third consisted of a comparison between the various configurations. The first part was completed at the beginning, the second after each measurement and the third after making the fourth measurement. This has been repeated both internally and externally (except the first part that was compiled only once).

General part

On average, the twelve choristers who took part in the mearurements are 26 years old. Six students of the three-years course, three of the magistral, a researcher and a professor. Ten singers also had experience with other choirs and six took singing lessons (from eight years to a few lessons). Seven said they heard their voice well when they sang in the choir; two almost always; one not much; another claims to hear his voice well in the *Sedicetto* but not in the large choir, while another states that it depended in the place.

The four choristers who wore the microphones claimed to have sung normally despite the microphones and that their presence did not change the sound.

Second part

In this part we can cnsider the following two questions.

“Did you find it easy to sing your part in the current choir position?”

By counting the votes, as regards the measurements carried out in the Courtyard, we have the following assessments: In nine they found it easy to sing their part in the first and third configuration, in ten in the second and only eight in the fourth. In general, therefore, it can be stated that the best configuration, in this case, was the second configuration. Considering the votes of the individual sections: for the Sopranos the configuration that received the most votes was the first; for the Altos ones the second; Tenors did well in all configurations while Bass found better in the first three.

As for the Aula Magna, instead, everyone found it easy to sing their part in the third configuration, while the least voted was the first. Considering the votes of the individual sections: as for the Sopranos, the configuration with the most votes was the third, in which all three were fine; the Altos preferred the last three configurations; the Tenors found themselves well in all configurations; Basses preferred the last two.

"Were you able to listen/monitor your voice well?"

Considering the measurements taken outside, everyone in the second configuration was able to listen/monitor their voice well; the one with the least votes was the fourth (with ten total votes). Considering the votes of the individual sections: Sopranos did well in all four configurations; for the Altos the configuration with the most votes was the second, which had a positive vote by all three singers; the two Tenors listened/monitored their voices well in all configurations; the Basses, overall, preferred the first three configurations.

As for the measurements made in the Aula Magna, the configurations with the highest marks were the second and fourth. Considering the votes of the individual sections: in particular one of the three Sopranos failed to hear/monitor his voice in any of the four configurations; fort he other Sopranos in the first, second and fourth they were able to listen/monitor their own voice; as for the Altos, everyone was able to hear/monitor their own voice in the fourth configurations; the two Tenors have positively evaluated all four configurations; the Basses, on the other hand, positively evaluated the second, third and fourth configurations.

Third part

The criterion for shell optimization was based on the results of the third part of the questionnaires. For quiestions 18 to 21 each chorister was asked to evaluate the configurations by placing a cross on a line. The result was then measured on a scal from 0 to 10 based on the position of the cross. It was decided to take into consideration the measurements that on average had a score higher than 5 and then make a count of the votes.

“In which position of the choir did you find it easier to sing your part?”

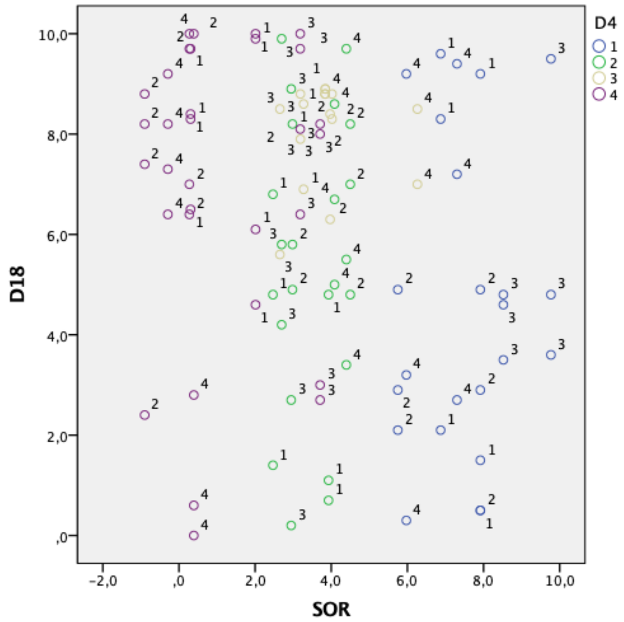
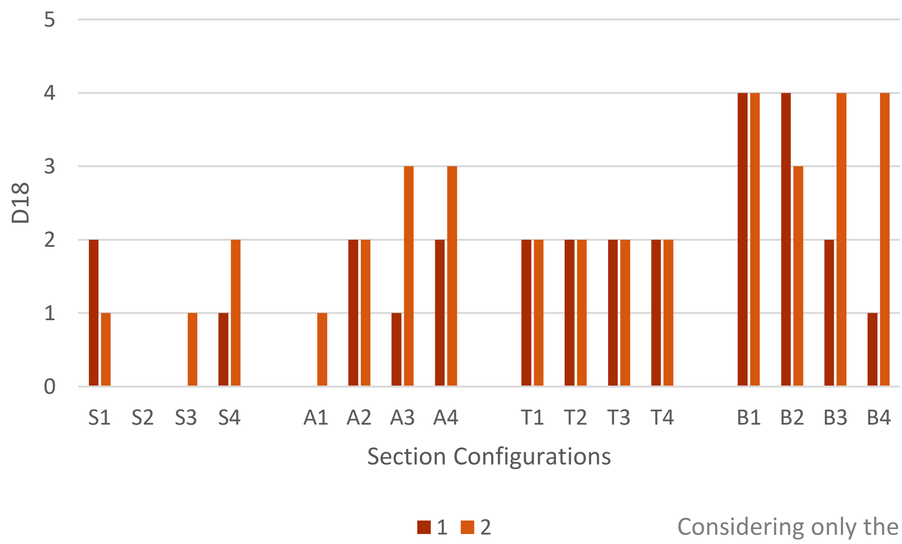


Figure 84 Answers to question number 18 with all the results

The chart on the side shows the answers to question 18. The blue, green, yellow and fuchsia dots correspon respectively to the four sections: Soprano, Alto, Tenor and Bass. The SOR value is represented in the x-axis, while the evaluation expressed by the chorister is shown in the y-axis. The numbers represent the four configurations. This graph includes both internal and external data.

The graph below, instead, represents the count of votes greater than five. Legend “1” (red colour) refers to measurements taken outdoors, while “2” (orange colour) refer to measurements taken indoors.



Considering only the values >=5
1: Measurements made in the courtyard;
2: Measurements made in the Aula Magna;
S*n*: Number measurement of Soprano;
A*n*: Number measurement of Alto;
T*n*: Number measurement of Tenor;
B*n*: Number measurement of Bass.

Figure 85 Count of votes for configurations with a grade higher than five for question 18.

Considering this last bar chart we note that in the Aula Magna the Soprano preferred the configuration number four, while the worst is the second. In external, instead, he preferred the first, while the worst were the second and third. For Alto, however, we note that in the courtyard the preferred configurations were the second and fourth while the worst was the first. This configuration was also the worst in the Aula Magna while the best were the thirs and fourth. For

Tenor in this case there were no preferences as all configurations had the same score. For bass the best were the first and the second on the outside while the worst was the fourth. In the Aula Magna we note that the second configuration is worst, while the other have had an equal score.

“How would you rate the choral sound in the positions adopted?”

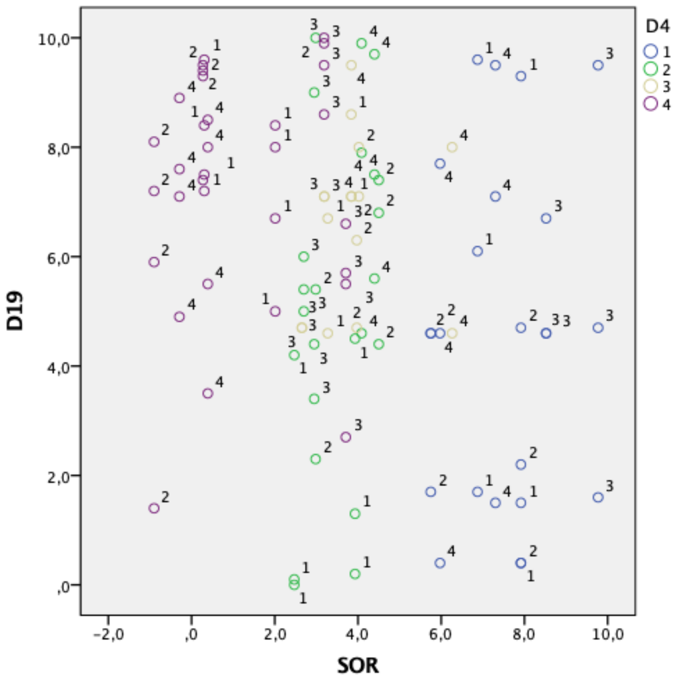
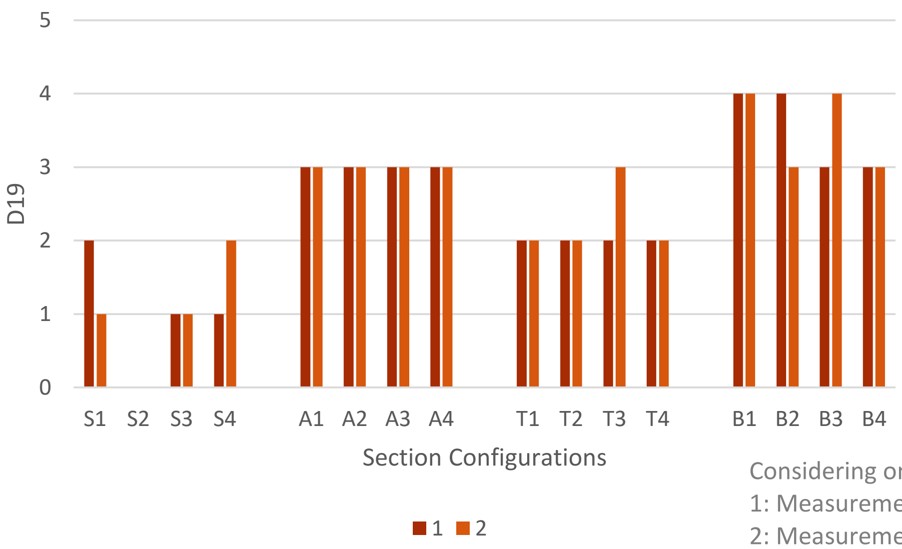


Figura 86 Answers to question number 19 with all the results



Considering only the values >=5
1: Measurements made in the courtyard;
2: Measurements made in the Aula Magna;
S*n*: Number measurement of Soprano;
A*n*: Number measurement of Alto;
T*n*: Number measurement of Tenor;
B*n*: Number measurement of Bass.

Figure 87 Count of votes for configurations with a grade higher than five for question 19.

For the Soprano we note that in the courtyard the preferred configuration was the first and the worst the second. This is worse also fot the measurements made in the Aula Magna, while the best, in this case, turns out to be the fourth. For Alto we note that there are no preferences for both the interior and the exterior as all configurations have the same score. The same thing also applies to the external condition of the Tenor whereas in the Aula Magna there is a preference for the configuration number 3; the other are, however, on an equal score. For Bass the best are the number one and two for the outside, while for Aula Magna one and three. In both cases the other two configurations are equal.

"How would you rate the position regarding the ease of listening to other sections?"

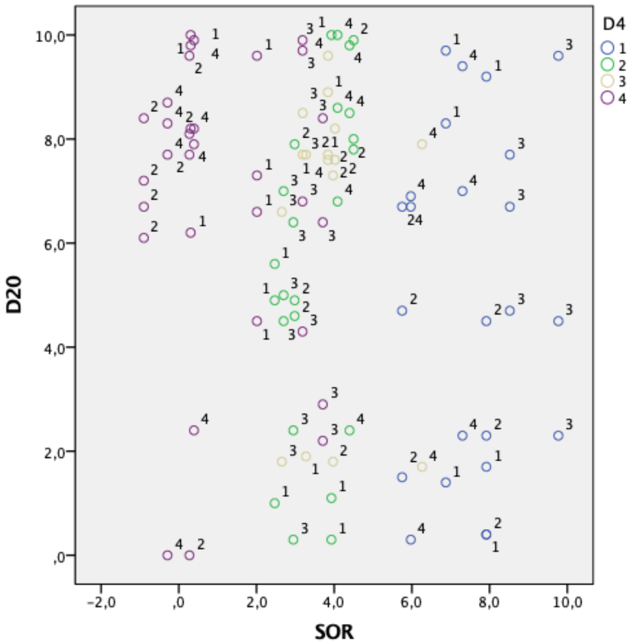
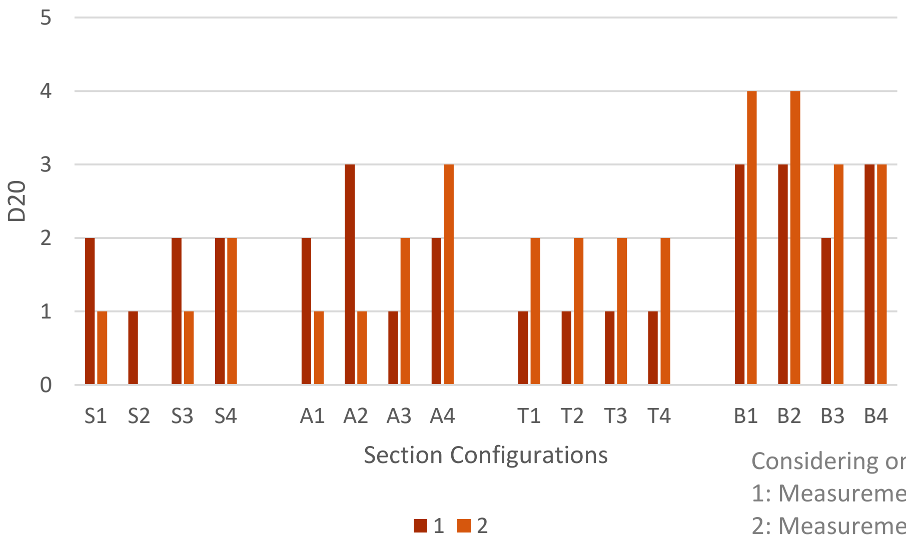


Figure 88 Answers to question 20 with all the results



Considering only the values >=5
1: Measurements made in the courtyard;
2: Measurements made in the Aula Magna;
S*n*: Number measurement of Soprano;
A*n*: Number measurement of Alto;
T*n*: Number measurement of Tenor;
B*n*: Number measurement of Bass.

Figure 89 Count of votes for configurations with a grade higher than five for question 20.

Considering the measurements of the Soprano made in the courtyard the worst is the second while the others have the same score. For the measurements made in the Aula Magna the worst, also in this case, is the second while the best corresponds to the fourth. Fort the Alto on the outside the best configuration is the second while the worst is the third; for the measurements taken in Aula Magna, the fourth configuration is the best, while the worst are the first and second. For Tenor, both internal and external all configurations have the same score. For the Bass, instead, the worst in the outside turns out to be the third, while the other three have the same score; for the measurements in the Aula Magna, on the other hand, the best are the first and second ones while the worst ones, on a par with each other, are the third and fourth.

"In which position did yuo prefer to sing?"

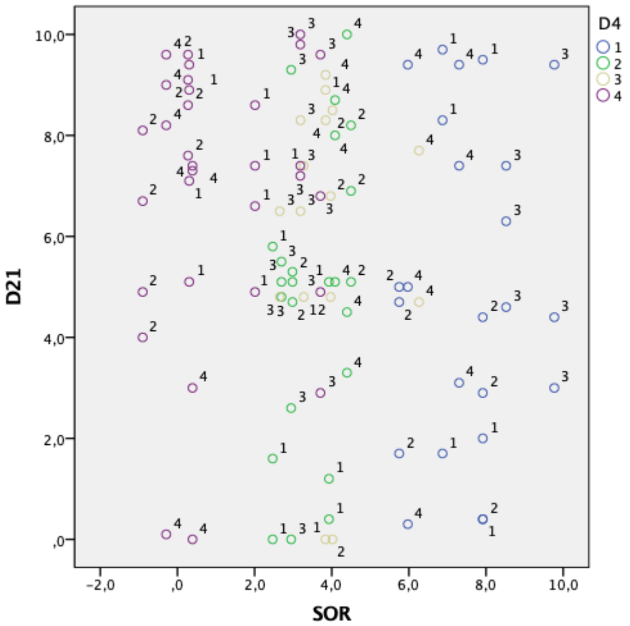
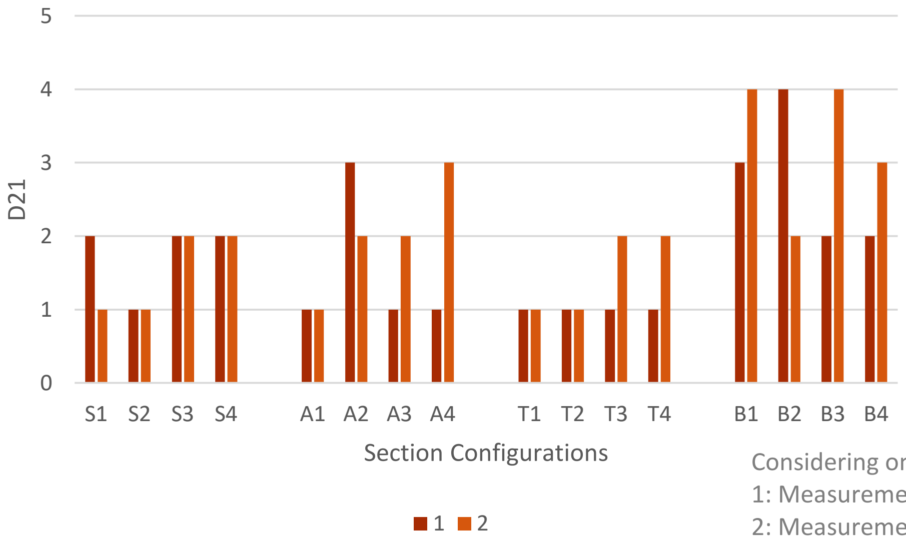


Figure 90 Answers to question 21 with all the results



Considering only the values >=5
1: Measurements made in the courtyard;
2: Measurements made in the Aula Magna;
S*n*: Number measurement of Soprano;
A*n*: Number measurement of Alto;
T*n*: Number measurement of Tenor;
B*n*: Number measurement of Bass.

Figure 91 Count of votes for configurations with a grade higher than five for question 21.

Considering the answer to question 21, it is noted that the Soprano does not have a preferred configuration outside, since the first, third and fourth have the same score (the secondi s the least preferred one). As for the Aula Magna, instead, the two configurations in which he preferred to sing are the third and fourth. Alto on the outside, instead, preferred to sing in the configuration number two, while for the condition in the Aula Magna the number four. For the Tenor, outside, the best ones were the number three and four while in the Aula Magna all four configurations had the same score. For Bass, the best configuration appears to be the secondo ne outside, while the first and third in the Aula Magna.

Questions 22 through 24, on the other hand, were crossover questions that compared the four measurements. In this case a count was taken of the votes taken from each configuration based on the sections, on the outside and inside condition.

"In which position were you, in general, able to better listen/monitor your voice?"

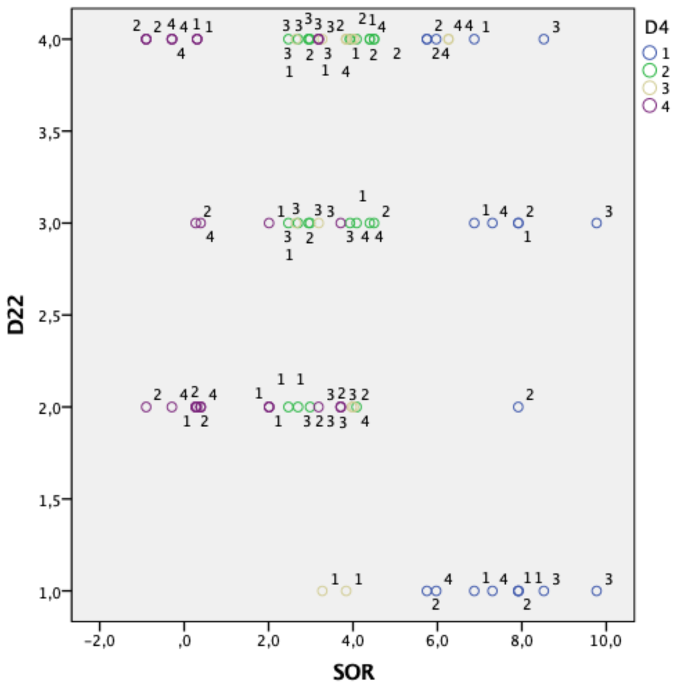


Figure 92 Answers to question 22 with all the results

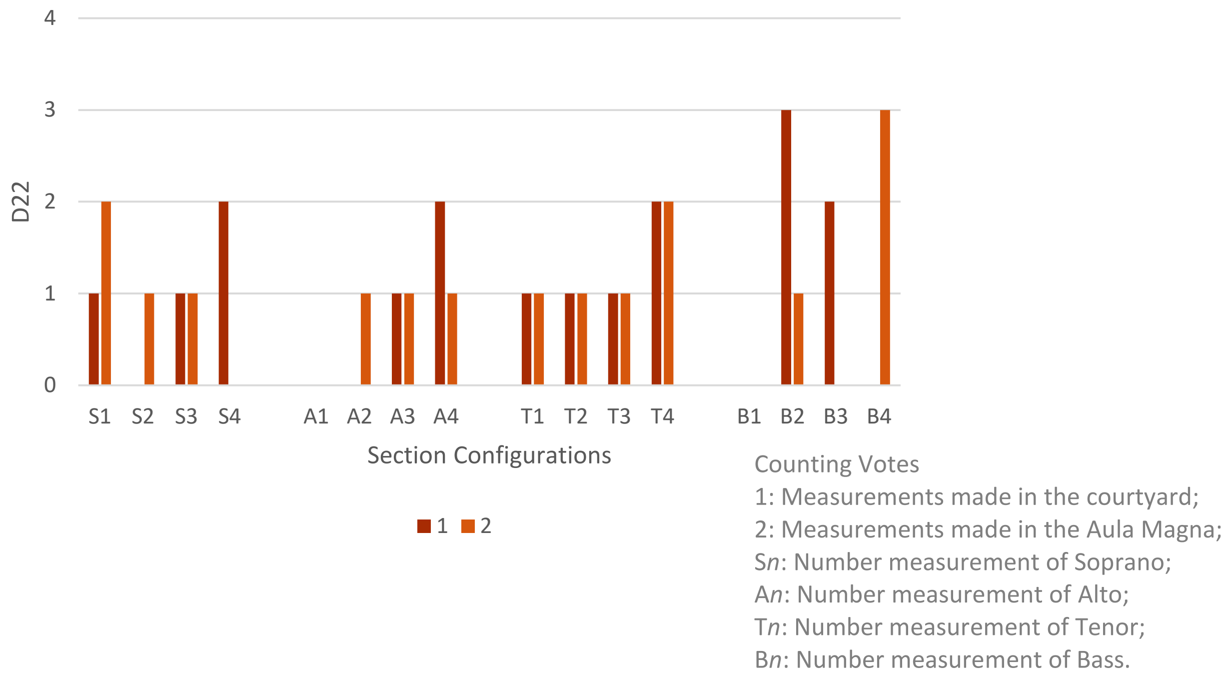
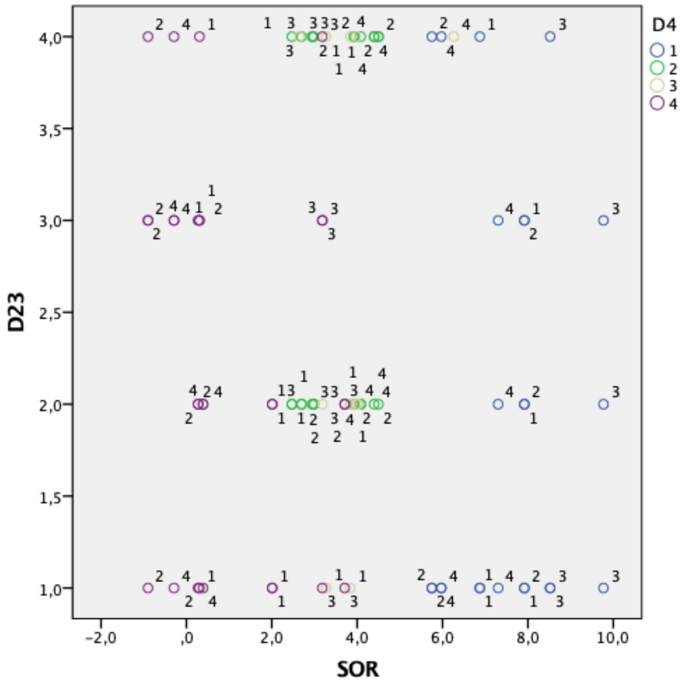
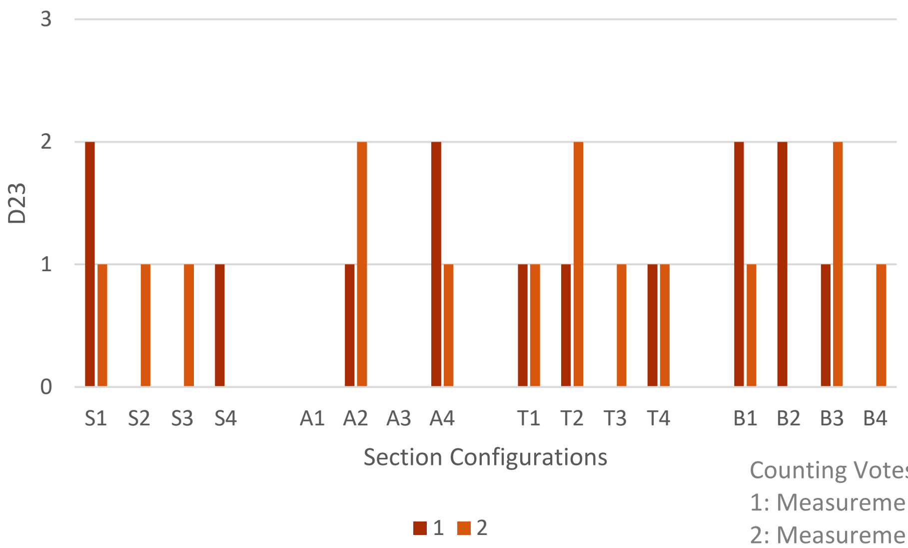


Figure 93 Answers to question 22

In this case we note that for the Soprano in the courtyard the best configuration was the number four while in the Aula Magna it was found to be the worst. In this case the best is the first one. The worst in the courtyard, however, is the second configuarion. Considering the Alto section, we immediately notice that the first one is the worst both in the Aula Magna and in the courtyard (in this case also the secondo ne has no vote higher than five). As for the best in the courtyard it appears to be the four configuration, while in Aula Magna is a situation of equal merit. For Tenor section we find the same context both in the Aula Magna and in the courtyard. The best is the fourth configuration, while the others have an equal score. For the Bass section the first configuration appears is worse both in the internal and external context; in the first case there is also the fourth configuration which falls into the worst, while in the second case the third. With regard to the major configuration, the number three prevails on the outside context, while the number four is on the inside context.

"In which position were you able to better listen/monitor the sound of the choir as a whole?"

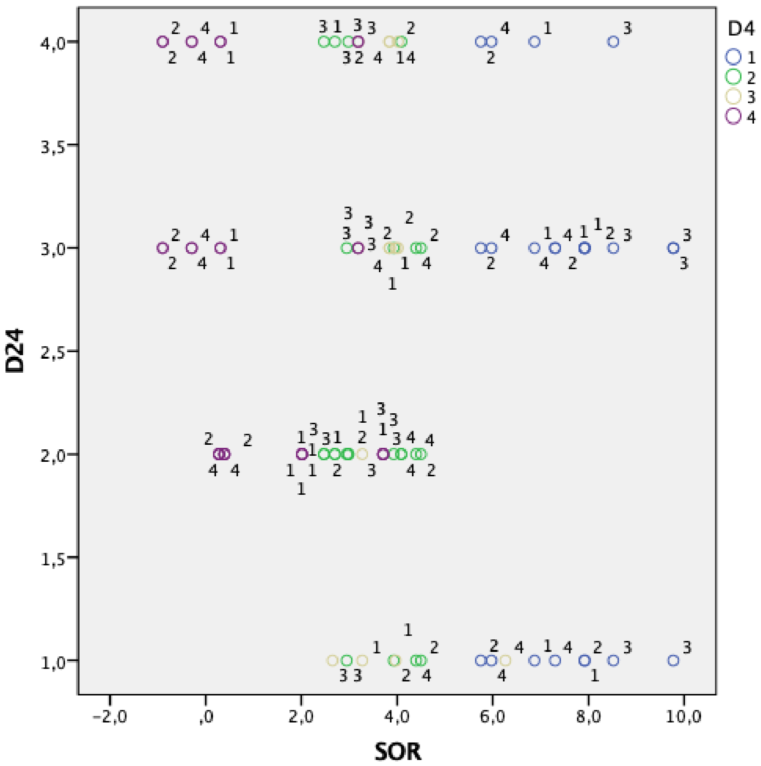


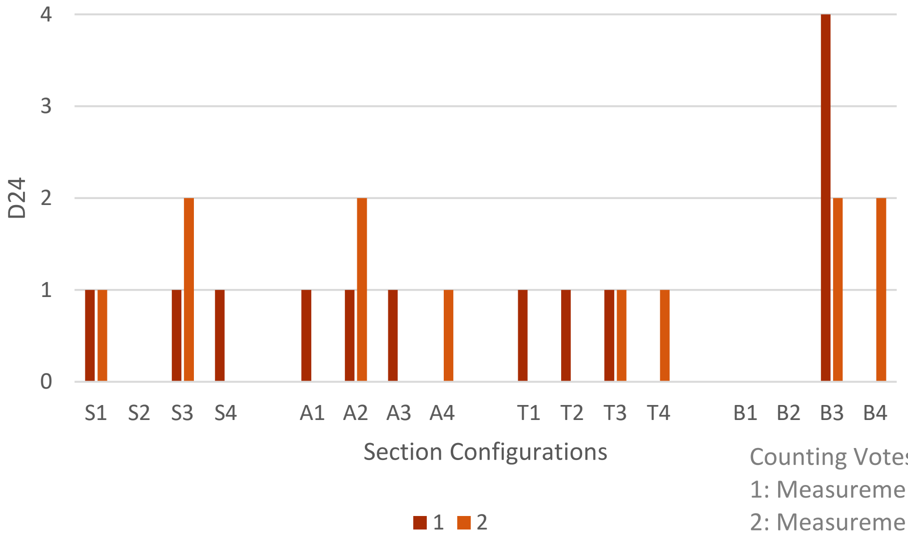


Counting Votes
1: Measurements made in the courtyard;
2: Measurements made in the Aula Magna;
S*n*: Number measurement of Soprano;
A*n*: Number measurement of Alto;
T*n*: Number measurement of Tenor;
B*n*: Number measurement of Bass.

In this case we note that for the Soprano in the courtyard the best configuration was the number one, instead in Aula Magna the worst is the fourth while the others are tied. The worst in the courtyard, however, are the second and third configuation. As for the Alto, we note that in the courtyard the best is the fourth while the worst are the first and third (as for the Aula Magna). In the Aula Magna the best is the second configurations. For the tenor in the courtyard the worst is the third while the others are tied. In the Aula Magna, instead, the best it is the second while the others are tied. For the bass, the best are the first and the second for the courtyard, while the third for the Aula Magna. The worst, instead, are the fourth for the courtyard and the second for the Aula Magna.

"In what position do you think the choir produced the best sound?"





Counting Votes
1: Measurements made in the courtyard;
2: Measurements made in the Aula Magna;
S*n*: Number measurement of Soprano;
A*n*: Number measurement of Alto;
T*n*: Number measurement of Tenor;
B*n*: Number measurement of Bass.

For the Soprano in the courtyard the worst configurations is the second, while the others are tied. As for the Aula Magna, the best is the third and the worst the second and fourth. For the Alto, the worst is the configuration number four while the others are tied. As for the Aula Magna, instead, the best is the second and the worst are the first and third. For the Tenor in the courtyard, we note that the worst is the number four while the others are tied. In the Aula Magna, on the others hand, the worst are the first and second configurations while the other two are tied. For the bass, in the courtyard, we see that everyone voted for the third configuration; for the Aula Magna, however, the best are the third and fourth.

Summarizing the votes of this third part we have the following results for Aula Magna

AulaMagna	**Best_Config**	**Worst_Config**
Soprano	4	2
Alto	4	1
Tenor	3-4	1
Bass	3	2

Table 45 Better and worst configurations based on the various sections (Aula Magna)

Regarding the condition outside we have the following preferences

Courtyard	**Best_Config**	**Worst_Config**
Soprano	1	2
Alto	2	1
Tenor	4	/
Bass	2	4

Table 46 Better and worst configurations based on the various sections (Courtyard). The Tenor has a preference for the fourth configuration, while the other three are tied

6.4 DESIGN

The design is based on the optimization of the SOR parameter in the Aula Magna condition. Starting from the configurations evaluated as *"Worst"* we tried to optimize them based on those considered to be the best. In the following two tables, the SOR obtained in the configurations examined can be compared.

AulaMagna	**Worst_Config**	**SOR**
Soprano	2	+7.91
Alto	1	+2.47
Tenor	1	+3.84
Bass	2	-0.90

Table 47 SOR values measured in the configurations considered the worst

AulaMagna	**Best_Config**	**SOR**
Soprano	4	+7.30
Alto	4	+4.09
Tenor	3; 4	+3.19; +3.84
Bass	3	+3.18

Table 48 SOR values measured in the configurations considered the best

As can be seen from the results reported above, the Alto and Bass need a higher SOR value, hence an increase of the *Self*.

The following picture shows the positions of the four singers in the worst position. Note that everyone is in the front row; as previously mentioned, comparing the SOR values in these positions there are, on fact, smaller values than those calculated in the row behind.

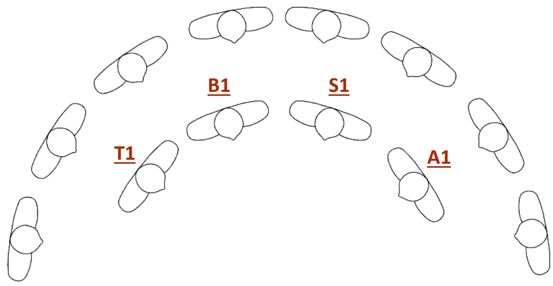


Figure 94 Positioning of the choristers in the worst rated positions

6.4.2 Methodology

The methods used are the following: *Image Source* and *Ray Tracing*.

6.4.2.1 Image Source

(21) The reflected wave is considered as a wave coming from the real image of the virtual source; it is considered as a direct wave originating from a fictitious source coinciding with the virtual image placed behind the surface responsible for reflection.

The hypotheses to consider are the following:

1. The approximations of geometric acoustics apply;
2. On the contour surfaces the sound is mirrored;
3. Each virtual reflection is associated with a virtual source that behaves in emission like the real source from which it originated;
4. Each source emits spherical wave fronts;
5. The propagation of spherical wave fronts is traceable by sound beams that go from the source to the receiver;
6. The sound power reaching the receiver is equal to that emitted by the decreased source.

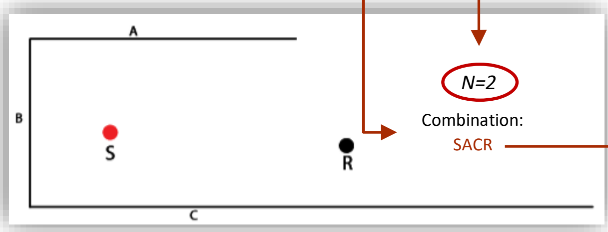
To identify the sound beams emitted by a source it is necessary to construct the mirror images of order *n* of the source with respect to all the walls that delimit the considered space. The visibility test is then carried out: the image sources visible for each receiving point are examined. Adding all the audible contributions we obtain the echogram; each contribution must be multiplied by the factor that determines the energy absorbed by the walls and normalized by a factor of $\frac{1}{r^2}$ due to the distance of the image source - receiver. Having n surfaces present you will have *n* possible images of the first order. Each can generate *n-1* second-order images. Considering the i-th generic order, then we will have

$$N_s = 1 + \frac{n}{n-2}((n-1)^j - 1) \approx (n-1)^j$$

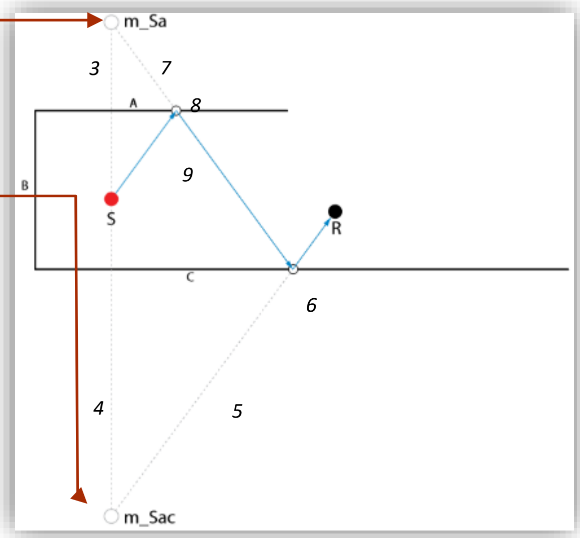
For each individual receiver, the energy shares from all the virtual sources must be added together and the sum is repeated for all the sources present.

(26) The image source method can be defined based on the following operating scheme:

1. Define the number of bounces (N);
2. Choose a combination;



Choosing this combination the source will be projetcted with respect to wall A (first bounce), then with respect to wall B (second bounce).



3. Mirror the source with respect to the first surface on the basis of the chosen combination (m_Sa);
4. Mirror the mirrored source with respect to the second surface (m_Sac);
5. Draw the line between the receiver and the last mirrored source;
6. Mark the intersection with the last intersected surface;
7. Draw a line between the intersection point and the first mirrored source;
8. Mark the intersection with the first intersected surface;
9. Draw a polyrage between the points;
10. Repeat the process for each combination.

The following table summarizes some features of this method

Stop options	Information obtained	Applicability conditions	Limits
The order of reflection has reached the predetermined value	Overall sound energy density in steady state	Sources and receivers must be internal to the environment	Very short ecograms
The remaining sound intensity in the nearest receiver is less than the set minimum	Sound level according to position and time	Reflection point must belong to the reflection surface	Minimum number of walls
	Sound intensity as a function of position and time	The radius must not be interrupted by a surface not involved in the reflection	Environments with a parallelepiped shape
	Delay times and arrival directions of the individual reflections		

Table 47 Features of Image Source

6.4.2.2 Ray Tracing

(21) In this method it is admitted that the sound energy propagates in the fractional space along rectilinear trajectories or sound beams.

Basic hypothesis:

1. The approximations of geometric acoustics apply;
2. On the contour surfaces the sound is mirrored;
3. The sound energy of the source is quantized into a finite number of sound particles associated with sound beams;
4. Starting from the position of the source the rays propagate in all directions according to the laws of geometric acoustics;
5. The rays have an infinitesimal and constant section;
6. The rays lose energy;
7. In reception, the energy particles associated with the different beams can be added together.

The sound is radiated omnidirectionally from a source in the form of rays: each of them has a specific energy, propagates at the speed of sound and undergoes successive impacts with the surfaces that define the environment (each reflection takes into account the wall absorption).

The rules of acoustic geometry and therefore of specular reflection must be applied to the rays.

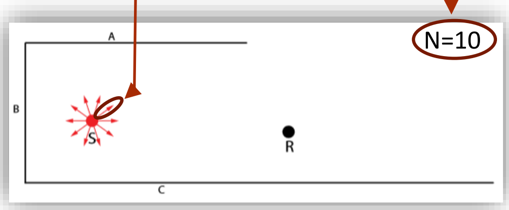
The listener, represented as a fictitious volume, is crossed by the reflected rays that are drawn from the source to the receiver.

The SPL sound pressure level is given by the energy contribution of the sound beams that pass through the listener.

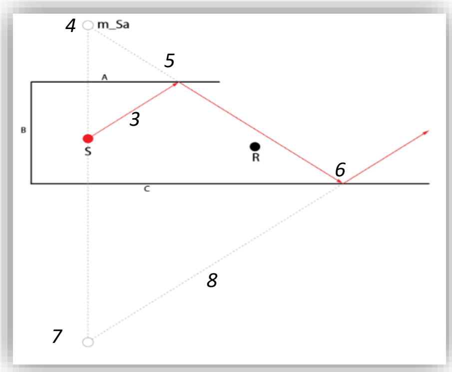
The power of each particle can be expressed in the following way $W = \frac{P_{wr}}{N_{rays}}$ rays. The particles traveling in the environment bounce off the boundary walls, therefore, with each reflection, the energy associated with the rays is progressively reduced based on the absorption coefficients. The sound power reaching the receiver is determined in successive time intervals as sums of a large number of small amounts of power carried by the rays that intercept the sphere of sensitivity.

(26) This method can be defined based on the following operating scheme:

1. Define the number of acoustic beams (N);
2. Choose a specific radius;



3. Extend the radius until it intersects a surface;
4. Mirror the source with respect to that surface (m_Sa);
5. Draw a line between the mirrored source and the intersection point;
6. Find the intersection with another surface;
7. Mirror the mirrored source with respect to this other surface;
8. Draw a line between the new mirrored source and the intersection point;
9. Find the intersection with a new surface: if it is not found repeat the steps for each beam.



The following table summarizes some features of this method

Stop options	Information obtained	Applicability conditions	Limits
Residual power of the beam has reached the preset limit	Overall sound energy density in steady state	The sound beams must hit the inner face of the contour surfaces	Lack of a rule to determine the number of rays to be drawn;
The order of reflection of the ray has reached a predetermined limit	Sound level according to position and time	The sound beams travel in front of the surfaces	Lack of a rule to determine the size of receivers
	Sound intensity as a function of position and time	Each reflection point must lie on its reflection surface	
	Delay times and arrival directions of the individual reflections		

Table 48 Features of Ray Tracing

6.4.3 Simulation

In the cad imported into Rhino, twelve omnidirectional sources have been inserted to which the following powers have been assigned (calculated on the basis of $\boldsymbol{W_i}$ obtained in the chapter 6.3.4)

	62.5	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
$\boldsymbol{L_w}$	84.8	84.8	85.0	85.5	85.5	86.0	86.3	86.4

At 15cm distance from each source the relative receivers have been positioned (one per source). The height taken into consideration for each singer is 1.65m. The sources, positioned as during the measurements, have an equivalent distance of 0.55cm.

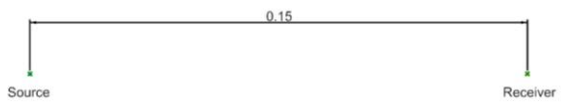


Figure 95 Receiver - Source distance (m)

For the simulation with the plugin *"Pachyderm"*, after importing the Rhino geometry into Grasshopper, the following settings have been entered: the first reflection order has been entered for the *Image Source*; for *Ray Tracing*, instead, a cut of time of 1000ms and a number of rays was initially set to 100 and then to "Minimum Convergence". In this way SPL_{Other} and SPL_{Self} were calculated for each singer.

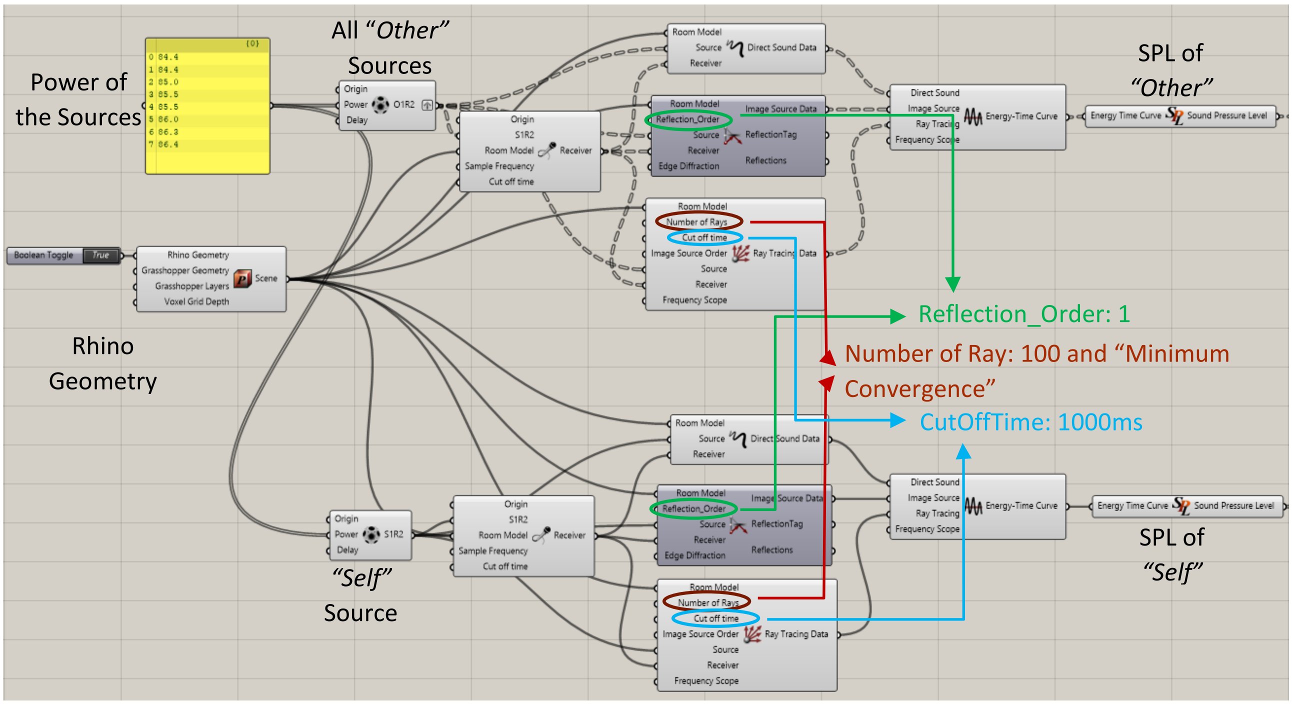


Figura 96 SOR calculation with Grasshopper and Pachyderm. Detail of the parameters used to set Image Source and Ray Tracing

Without the aid of the shell, from the simulation, we have the following results.

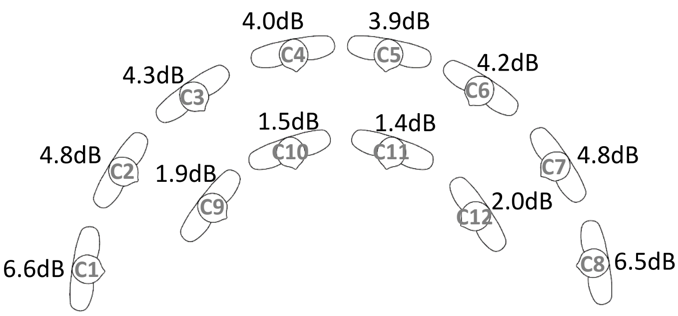


Figure 97 SOR values without the shell. Cn=nth chorister.

As you can see in the first row the SOR values are very low.

The following table details the SPL_{Other} and SPL_{Self}.

Chorister	SPL_{Other}_NoSt	SPL_{Self}_NoSt	SOR_NoSt
C1	+93.4dB	+100.0dB	+6.6dB
C2	+95.2dB	+100.0dB	+4.8dB
C3	+95.7dB	+100.0dB	+4.3dB
C4	+96.0dB	+100.0dB	+4.0dB
C5	+96.1dB	+100.0dB	+3.9dB
C6	+95.8dB	+100.0dB	+4.2dB
C7	+95.2dB	+100.0dB	+4.8dB
C8	+93.5dB	+100.0dB	+6.5dB
C9	+98.1dB	+100.0dB	+1.9dB
C10	+98.6dB	+100.1dB	+1.5dB
C11	+98.6dB	+100.0dB	+1.4dB
C12	+98.0dB	+100.0dB	+2.0dB

Table 50 Detail of Other and Self results without the aid of the shell.

It is noted that the *Other* increases in the central areas and in particular in the first row. Having an SPL_{Self} equal for all the singers, this causes a decrease in the *SOR*.

In order to increase the *Self* of the choristers in front, it was decided to design a structure that was above their heads (only above the heads of the choristers in the first row). The figure below shows the designed structure.

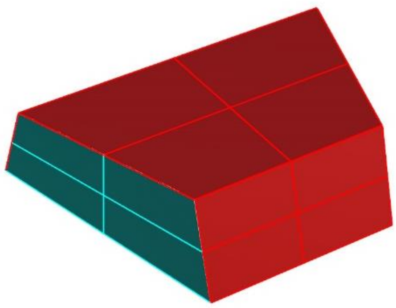


Figura 98 Design of the first structure. In red there are reflective panels and in blue there are absorbent panels

The red surfaces are reflective panels that have the task of reflecting the voice of the chorister on wich they are positioned. In detail, we have an upper panel set at 90° and two inclinate panels with the following measures

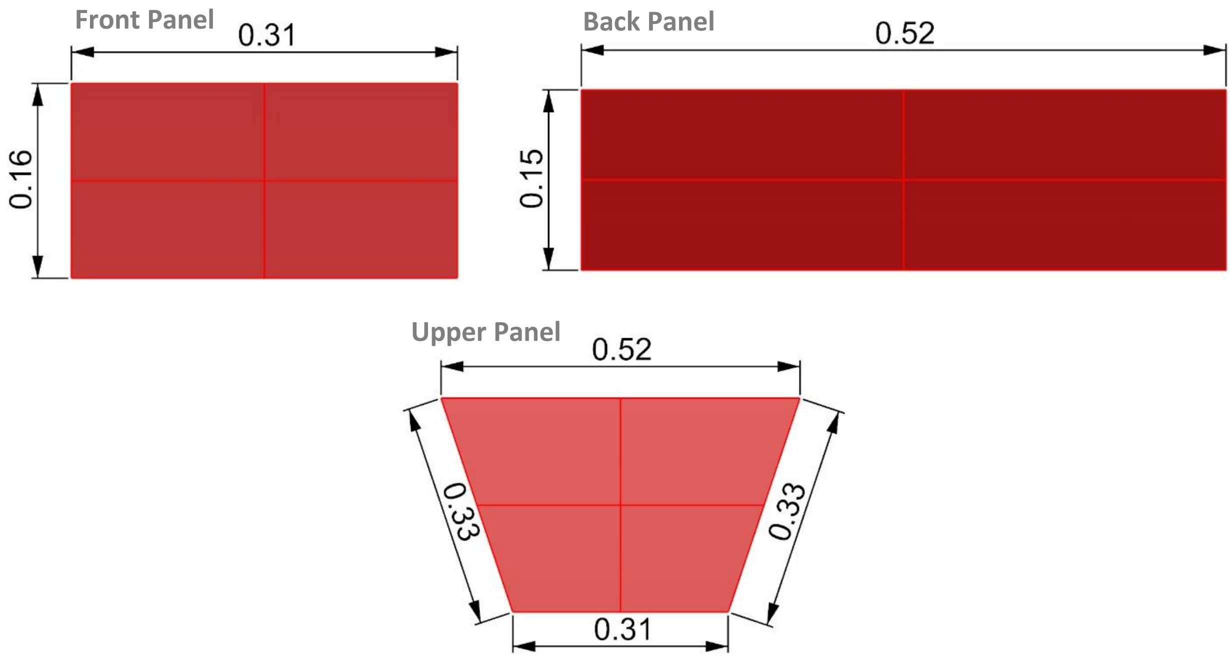


Figura 99 Dimensions of the three reflective panels (m)

The side panels (in blue) are absorbent and are used to schield the influence of *Other*.

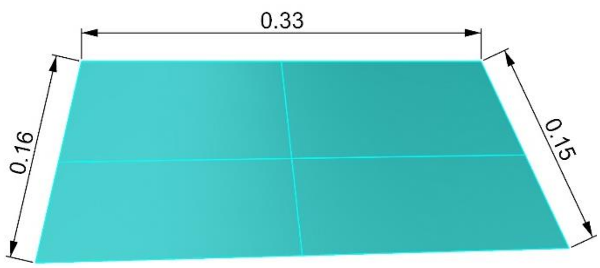


Figura 100 Dimensions of the absorbent panels (m)

With this structure above the subject's head (20cm away from the source), we have the following results:

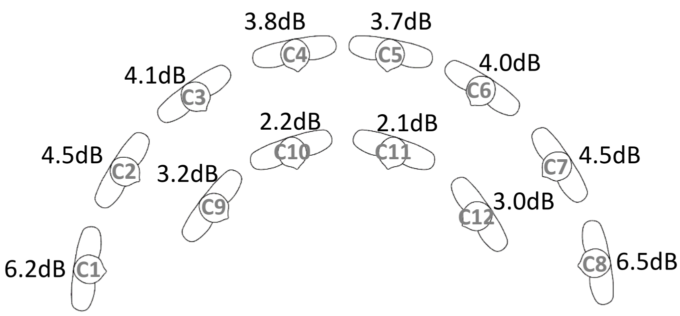


Figure 101 SOR values with the first design of panels placed at 20cm from the source. Cn=nth chorister.

Chorister	SPL_{Other}_St_1	SPL_{Self}_St_1	SOR_St_1
C1	+93.8dB	+100.0dB	+6.2dB
C2	+95.5dB	+100.0dB	+4.5dB
C3	+95.9dB	+100.0dB	+4.1dB
C4	+96.2dB	+100.0dB	+3.8dB
C5	+96.4dB	+100.0dB	+3.6dB
C6	+96.0dB	+100.0dB	+4.0dB
C7	+95.5dB	+100.0dB	+4.5dB
C8	+93.6dB	+100.0dB	+6.4dB
C9	+98.2dB	+101.4dB	+3.2dB
C10	+99.3dB	+101.5dB	+2.2dB
C11	+99.4dB	+101.5dB	+2.1dB
C12	+98.5dB	+101.5dB	+3.0dB

Table 51 Detail of Other and Self results with the first design

Considering the values without their help we have the following increments for the SPL_{Other}

Chorister	SPL_{Other}_NoSt	SPL_{Other}_St_1	Increment
C1	+93.4dB	+93.8dB	+0.4dB
C2	+95.2dB	+95.5dB	+0.3dB
C3	+95.7dB	+95.9dB	+0.2dB
C4	+96.0dB	+96.2dB	+0.2dB
C5	+96.1dB	+96.4dB	+0.3dB
C6	+95.8dB	+96.0dB	+0.2dB
C7	+95.2dB	+95.5dB	+0.3dB
C8	+93.5dB	+93.6dB	+0.1dB
C9	+98.1dB	+98.2dB	+0.1dB
C10	+98.6dB	+99.3dB	**+0.7dB**
C11	+98.6dB	+99.4dB	**+0.8dB**
C12	+98.0dB	+98.5dB	+0.5dB

Table 52 Increase of the Other SPL. SPLOther_NoSt: indicates the results without the aid of the structure. SPLOther_St_1: indicates the results with the structure

We note that in the two central choristers in the first row (C10 and C11) there is a greater increase than other choristers.

As for the SPL_{Self} the increases are shown in the table below

Chorister	SPL_{Self}_NoSt	SPL_{Self}_St_1	Increment
C1	+100.0dB	+100.0dB	+0.0dB
C2	+100.0dB	+100.0dB	+0.0dB
C3	+100.0dB	+100.0dB	+0.0dB
C4	+100.0dB	+100.0dB	+0.0dB
C5	+100.0dB	+100.0dB	+0.0dB
C6	+100.0dB	+100.0dB	+0.0dB
C7	+100.0dB	+100.0dB	+0.0dB
C8	+100.0dB	+100.0dB	+0.0dB
C9	+100.0dB	+101.4dB	+1.4dB
C10	+100.1dB	+101.5dB	+1.4dB
C11	+100.0dB	+101.5dB	+1.5dB
C12	+100.0dB	+101.5dB	+1.5dB

Table 53 Increase of the Self SPL. SPLSelf_NoSt: indicates the results without the aid of the structure. SPLSelf_St_1: indicates the results with the structure

Note that in the second row there are no increments, while in the first row the first two choristers (C9 and C10) have an increase of +1.4dB, instead the other two (C11 and C12) an increase of +1.5dB.

Now we can see the increments about the SOR value in the following table.

Chorister	SOR_NoSt	SOR_St_1	Increment
C1	+6.6dB	+6.2dB	-0.4dB
C2	+4.8dB	+4.5dB	-0.3dB
C3	+4.3dB	+4.1dB	-0.2dB
C4	+4.0dB	+3.8dB	-0.2dB
C5	+3.9dB	+3.6dB	-0.3dB
C6	+4.2dB	+4.0dB	-0.2dB
C7	+4.8dB	+4.5dB	-0.3dB
C8	+6.5dB	+6.4dB	-0.1dB
C9	+1.9dB	+3.2dB	+1.3dB
C10	+1.5dB	+2.2dB	+0.7dB
C11	+1.4dB	+2.1dB	+0.7dB
C12	+2.0dB	+3.0dB	+1.0dB

Table 54 Increase of the SOR. SOR_NoSt: indicates the results without the aid of the structure. SOR_St_1: indicates the results with the structure

We note that the SOR in the rows behind decreases a little, while in the front row increases. The gratest increases occurs in C9 with a +1.3dB. The SOR relating to the two central singers in the front row still remain in a bit low. To try to increase the SOR of these choristers placed in the center, it was decided to extend the absorbent side panels.

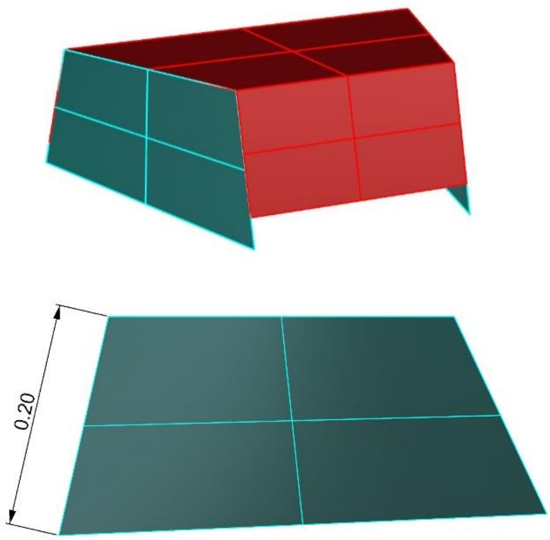


Figura 102 Extension of the side absorbent panels in length. This allows you to further shield the sound of Other. (Size in m)

Increasing the length of the absorbent side panels (blue) slightly (from 0.16m to 0.20m) shows an increase in the SOR in the two central singers in the first row.

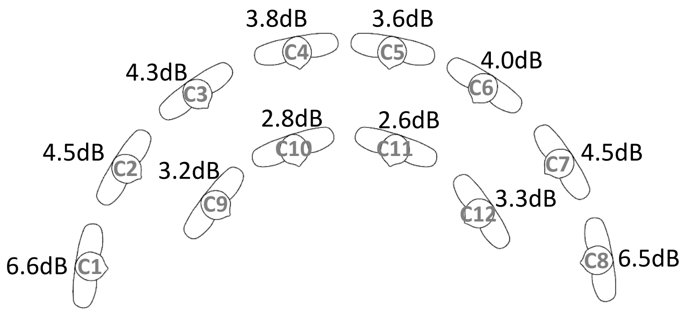


Figure 103 SOR values with the elongation of the absorpent panels.
Cn=nth chorister.

Chorister	SPL_{Other}_St_2	SPL_{Self}_St_2	SOR_St_2
C1	+93.4dB	+100.0dB	+6.6dB
C2	+95.5dB	+100.0dB	+4.5dB
C3	+95.7dB	+100.0dB	+4.3dB
C4	+96.2dB	+100.0dB	+3.8dB
C5	+96.4dB	+100.0dB	+3.6dB
C6	+96.0dB	+100.0dB	+4.0dB
C7	+95.5dB	+100.0dB	+4.5dB
C8	+93.5dB	+100.0dB	+6.5dB
C9	+98.2dB	+101.4dB	+3.2dB
C10	+98.7dB	+101.5dB	+2.8dB
C11	+98.9dB	+101.5dB	+2.6dB
C12	+98.2dB	+101.5dB	+3.3dB

Table 55 Detail of the results with the elongation of the absorbent panels

In detail, compared to the previous simulation, we have the following increments

Chorister	SPL_{Other}_St_1	SPL_{Other}_St_2	Increment
C1	+93.8dB	+93.4dB	-0.4dB
C2	+95.5dB	+95.5dB	0.0dB
C3	+95.9dB	+95.7dB	-0.2dB
C4	+96.2dB	+96.2dB	0.0dB
C5	+96.4dB	+96.4dB	0.0dB
C6	+96.0dB	+96.0dB	0.0dB
C7	+95.5dB	+95.5dB	0.0dB
C8	+93.6dB	+93.5dB	-0.1dB
C9	+98.2dB	+98.2dB	0.0dB
C10	+99.3dB	+98.7dB	**-0.6dB**
C11	+99.4dB	+98.9dB	**-0.5dB**
C12	+98.5dB	+98.2dB	-0.3dB

Table 56 Comparison of results in the previous simulation about the SPL of Other. SPLOther_St_1 indicates the values previously obtaine; while SPLOther_St_2 indicates the values obtained with the lengthening of the absorbent side panels.

It should be noted that the SPL of Other tends to decrease precisely in the two central choristers placed in the front row (C10 and C11). You may notice another minimal decrease in C1, C3, C8 and C12.

The following table shows the increments concerning the SPL_{Self}

Chorister	SPL_{Self}_St_1	SPL_{Self}_St_2	Increment
C1	+100.0dB	+100.0dB	+0.0dB
C2	+100.0dB	+100.0dB	+0.0dB
C3	+100.0dB	+100.0dB	+0.0dB
C4	+100.0dB	+100.0dB	+0.0dB
C5	+100.0dB	+100.0dB	+0.0dB
C6	+100.0dB	+100.0dB	+0.0dB
C7	+100.0dB	+100.0dB	+0.0dB
C8	+100.0dB	+100.0dB	+0.0dB
C9	+101.4dB	+101.4dB	+0.0dB
C10	+101.5dB	+101.5dB	+0.0dB
C11	+101.5dB	+101.5dB	+0.0dB
C12	+101.5dB	+101.5dB	+0.0dB

Table 57 Comparison of results in the previous simulation about the SPL of Self. SPLSelf_St_1 indicates the values previously obtaine; while SPLSelf_St_2 indicates the values obtained with the lengthening of the absorbent side panels.

Having changed only the absorbent sides slightly, we note tht there isn’t an increment in the SPL of *Self.*

Considering the SOR values, on the other hand, we have the following increments (with a costant Self and Other decrease leads to an increase of SOR).

Chorister	SOR_St_1	SOR_St_2	Increment
C1	+6.2dB	+6.6dB	+0.4dB
C2	+4.5dB	+4.5dB	+0.0dB
C3	+4.1dB	+4.3dB	+0.2dB
C4	+3.8dB	+3.8dB	+0.0dB
C5	+3.6dB	+3.6dB	+0.0dB
C6	+4.0dB	+4.0dB	+0.0dB
C7	+4.5dB	+4.5dB	+0.0dB
C8	+6.4dB	+6.5dB	+0.1dB
C9	+3.2dB	+3.2dB	+0.0dB
C10	+2.2dB	+2.8dB	+0.6dB
C11	+2.1dB	+2.6dB	+0.5dB
C12	+3.0dB	+3.3dB	+0.3dB

Table 58 Comparison of results in the previous simulation about the SOR. SOR_St_1 indicates the values previously obtaine; while SOR_St_2 indicates the values obtained with the lengthening of the absorbent side panels.

The increment of the SOR is better for the two central choristers in the first row (C10 and C11): +0.6dB and +0.5dB. Another particular case, is the first chorister in the first row: there isn't an increment for him. In this case, however, the goal was to suceed in increasing the SOR of the two central choristers. As can also be seen from the table below, their SOR was able to increase significantly. Taking into consideration, therefore, the data without the help of the shell, there are the following increments.

Chorister	SOR_NoSt	SOR_St_2	Increment
C1	+6.6dB	+6.6dB	+0.0dB
C2	+4.8dB	+4.5dB	-0.3dB
C3	+4.3dB	+4.3dB	+0.0dB
C4	+4.0dB	+3.8dB	-0.2dB
C5	+3.9dB	+3.6dB	-0.3dB
C6	+4.2dB	+4.0dB	-0.2dB
C7	+4.8dB	+4.5dB	-0.3dB
C8	+6.5dB	+6.5dB	+0.0dB
C9	+1.9dB	+3.2dB	+1.3dB
C10	+1.5dB	+2.8dB	+1.3dB
C11	+1.4dB	+2.6dB	+1.2dB
C12	+2.0dB	+3.3dB	+1.3dB

Table 59 Increase of the SOR

It should be noted that in all four choristers in the first row it is possible to have an increase of at leas +1dB. Other simulations carried out by increasing the length of these panels cause a continuous increase in SOR (especially for the two central choristers, which are increasingly isolated). In fact, in this case the extension was not going to cover the receiver. Going further to lengthen the sides (as in the figure) we have the following data

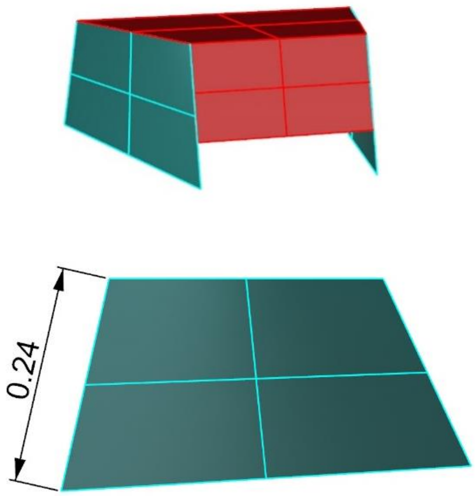


Figure 104 New dimension of the absorbent side

Chorister	SPL_{Other}_St_3	SPL_{Self}_St_3	SOR_St_3
C1	+92.0dB	+100.0dB	+8.0dB
C2	+94.7dB	+100.0dB	+5.3dB
C3	+94.5dB	+100.0dB	+5.5dB
C4	+95.1dB	+100.0dB	+4.9dB
C5	+95.4dB	+100.0dB	+4.6dB
C6	+96.5dB	+100.0dB	+4.5dB
C7	+94.6dB	+100.0dB	+5.4dB
C8	+92.4dB	+100.0dB	+7.6dB
C9	+95.2dB	+101.4dB	+6.2dB
C10	+95.9dB	+101.5dB	+5.6dB
C11	+96.3dB	+101.5dB	+5.2dB
C12	+96.8dB	+101.5dB	+4.7dB

Table 60 Detail of the results with the elongation of the absorbent panels

Having only gone to lengthen the absorbent sides, there is a clear decrease in the SPL of *Other* (both in the choristers of the first row and in the second row) with a consequent increase in the SOR.

Going to increase the distance between the panels and the source it is necessary to increase the inclination of the reflective panels. As can be seen from the table below, the SOR decreases with increasing the distance. In this case the panels were raised by another 20cm above the source (green point is the source, red point is the receiver).

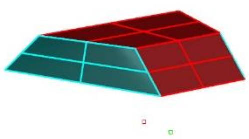


Figure 105 Increase head - structure distance.

Chorister	SPL_{Other}	SPL_{Self}	SOR
C1	+93.7dB	+100.0dB	+6.3dB
C2	+95.5dB	+100.0dB	+4.5dB
C3	+96.0dB	+100.0dB	+4.0dB
C4	+96.3dB	+100.0dB	+3.7dB
C5	+96.4dB	+100.0dB	+3.6dB
C6	+96.0dB	+100.0dB	+4.0dB
C7	+95.5dB	+100.0dB	+4.5dB
C8	+93.7dB	+100.0dB	+6.3dB
C9	+98.1dB	+100.6dB	+2.5dB
C10	+98.6dB	+100.6dB	+2.0dB
C11	+98.9dB	+100.6dB	+1.7dB
C12	+98.0dB	+100.8dB	+2.8dB

Table 61 Detail of the results deriving from the increase in the source panels distance

Also in this case the following table shows the increments with respect to the case without the aid of the shell.

Chorister	SOR_NoSt	SOR_DistancePanel	Increment
C1	+6.6dB	+6.3dB	-0.3dB
C2	+4.8dB	+4.5dB	-0.3dB
C3	+4.3dB	+4.0dB	-0.3dB
C4	+4.0dB	+3.7dB	-0.3dB
C5	+3.9dB	+3.6dB	-0.3dB
C6	+4.2dB	+4.0dB	-0.2dB
C7	+4.8dB	+4.5dB	-0.3dB
C8	+6.5dB	+6.3dB	-0.2dB
C9	+1.9dB	+2.5dB	+0.6dB
C10	+1.5dB	+2.0dB	+0.5dB
C11	+1.4dB	+1.7dB	+0.3dB
C12	+2.0dB	+2.8dB	+0.8dB

Table 62 Detail of the results deriving from the increase in the source panels distance

In this case we note that it is minor increase of the SOR compared to the previous structure (St_1). The largest increases are reported by lateral choristers (C9 and C12) which have an increase of +0.6dB and +0.8dB. The most disadvantaged is the chorister C11, which has an increase of only +0.3dB.

In other tests carried out, surfaces that served as monitor were studied. Although they were positioned at various distances and inclinations, they did not lead to increases in the the SOR parameter as they tendend to increase the SPL of Other as well. The following figures show some examples of the monitor taken into consideration.

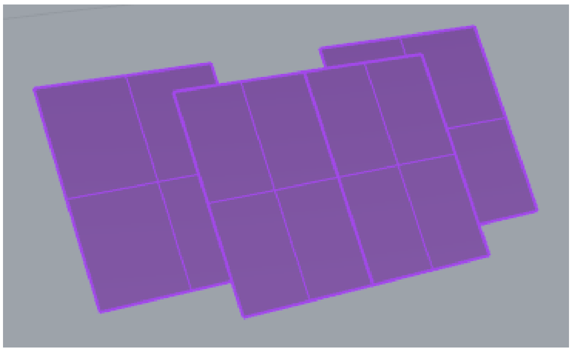


Figure 106 Monitor

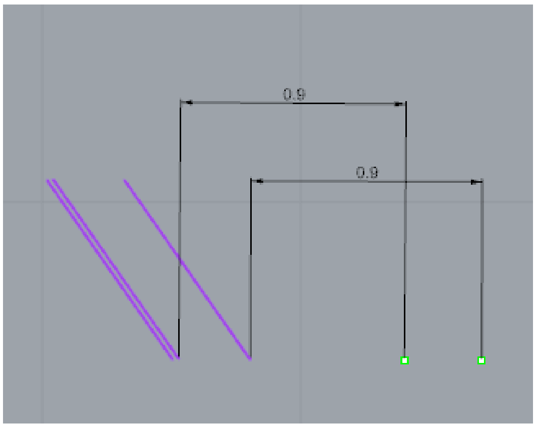


Figure 107 Distance between monitor and sources (in m)

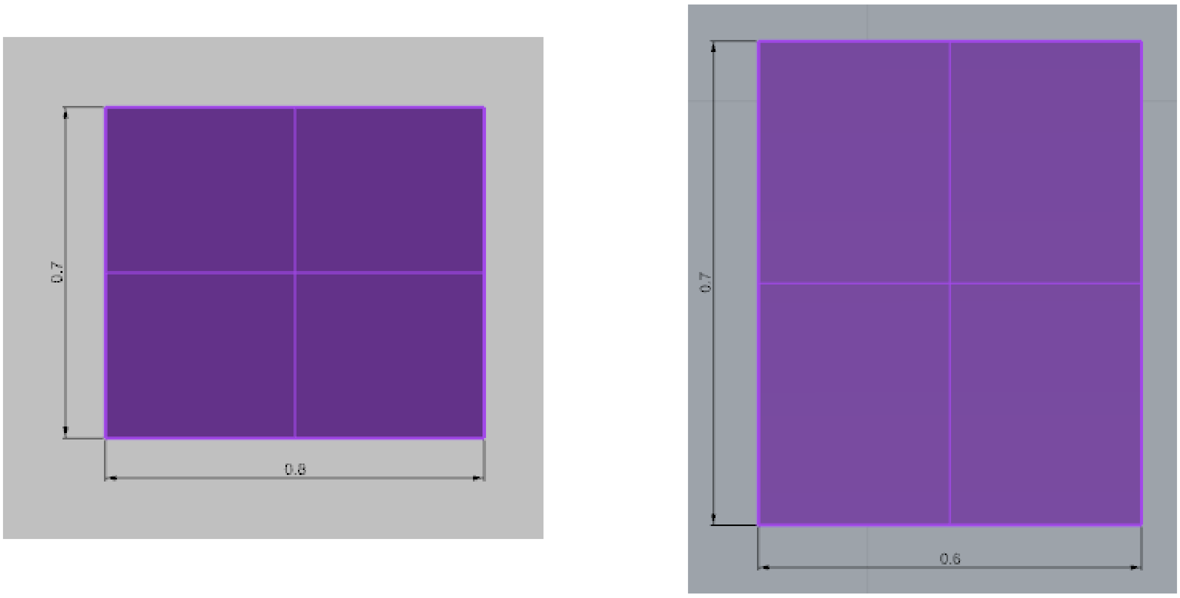


Figure 108 Dimension of the monitor

Chorister	SPL_{Other}_Monitor	SPL_{Self}_Monitor	SOR
C1	+93.5dB	+100.0dB	+6.5dB
C2	+95.4dB	+100.0dB	+4.6dB
C3	+95.9dB	+100.0dB	+4.1dB
C4	+96.2dB	+100.0dB	+3.8dB
C5	+96.3dB	+100.0dB	+3.7dB
C6	+95.9dB	+100.0dB	+4.1dB
C7	+95.4dB	+100.0dB	+4.6dB
C8	+93.6dB	+100.0dB	+6.4dB
C9	+98.2dB	+100.0dB	+1.8dB
C10	+98.7dB	+100.0dB	+1.3dB
C11	+98.7dB	+100.0dB	+1.3dB
C12	+98.1dB	+100.0dB	+1.9dB

Table 63 Detail of the results deriving from the monito

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