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SOUND WAVES

Can you hear me?

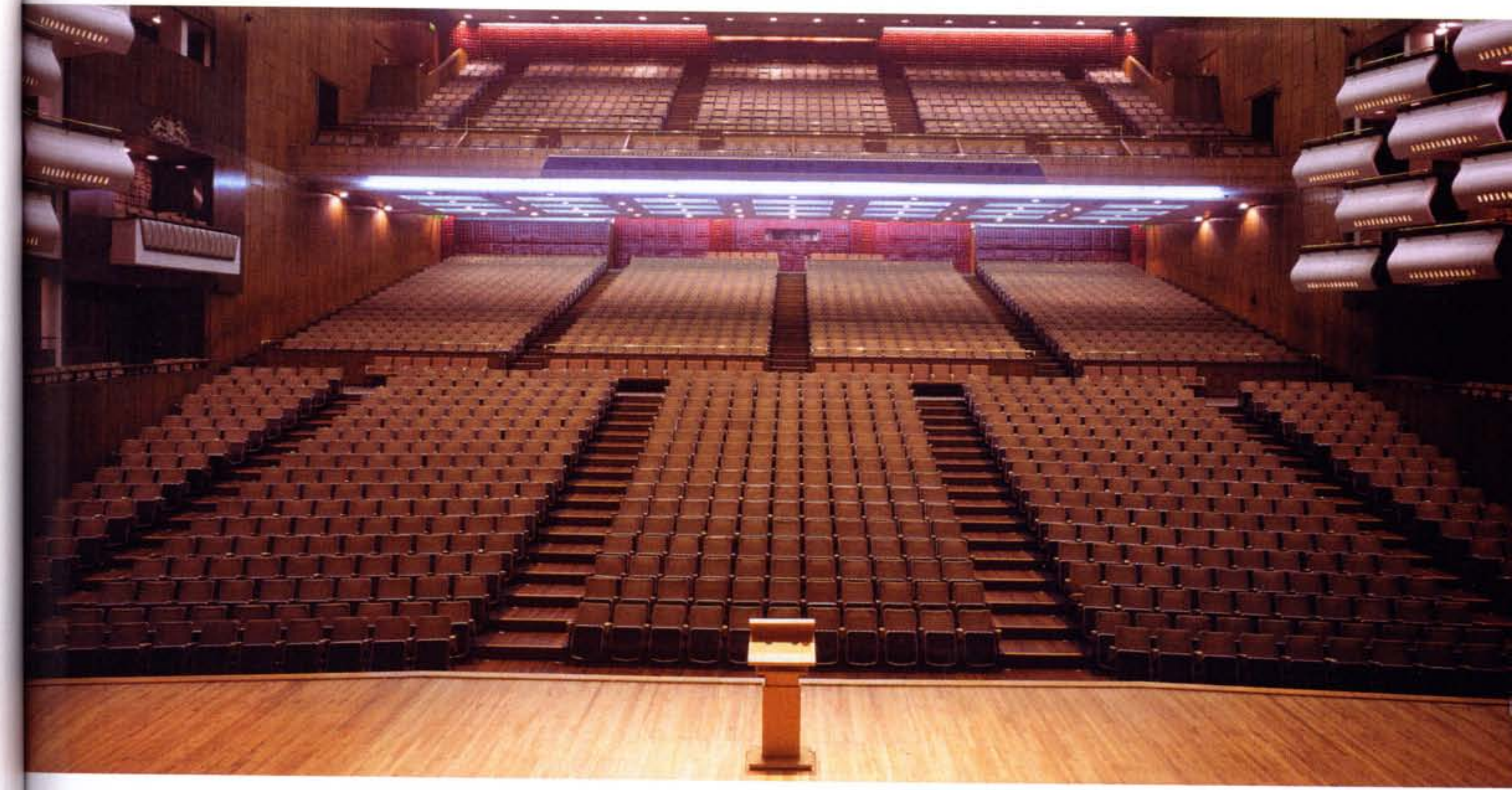
How does a violin project its sound to the far corners of a concert hall? In the first part of their series on violin acoustics, **Joseph Curtin** and **Martin Schleske** examine the evidence

Why do some violins project so much better than others? And what, in acoustical terms, allows them to do this? To investigate this let's go first to the Rhineland, in Germany, where researcher Ute Loos carried out a series of experiments in a small Düsseldorf concert hall.

Loos began by asking six violin students to play a series of unaccompanied scales and musical extracts. The students, who played on their own instruments, were recorded by three microphones – the first located beside the player's ear, the second a metre away and the third twelve metres away. The subject under investigation was projection, which clearly involves objectively measurable quantities, such as sound pressure, along with more difficult to measure things, such as our subjective sense of loudness. Players and makers are familiar with the odd independence between how loud an instrument sounds under the ear and how loud it sounds at a distance. Yet, while players vary considerably in how much sound they can tolerate under the ear, they vary little in their requirement that an instrument should project. Like response and dynamic range, projection can be considered an 'absolute' quality – the more the better. Violinists may complain that an instrument is too bright, too dark, too mellow or too harsh, but never that it projects too well. Though projection is not yet fully understood at a scientific level, a preliminary investigation seems a good place to begin these articles.

The term 'violin' will often be used to represent the entire instrument family. This is partly a matter of convenience and partly a reflection of the paucity of research on violas, cellos and basses. Many of the findings, however, can be extended to the larger instruments. If projection involves at the very least getting the sound to radiate beyond the immediate vicinity of the violin, then comparing the signals from the under-ear microphone with the one at twelve metres should yield some kind of objective measure. Loos found that, depending on the instrument, the loudness at twelve metres was between one quarter and one sixth of the loudness under the player's ear. In other words, the ratio of the loudness at one metre to that at twelve varied by as much as 50 per cent. Interestingly, when she compared the loudness at twelve metres with that at one metre (rather than that under the ear), the differences between the instruments vanished; loudness in all cases dropped by about half. Why?

The violin body, when played, subdivides into numerous vibrating areas, each of which creates pressure waves in the adjacent air. Left to themselves, the



ABOVE London's Royal Festival Hall holds 2,600 people. In which seat do you hear the violin best?

pressure waves leave the area at about 340 metres per second – the speed of sound in air. Because the vibrating areas are often out of phase with one another – one moving up while another moves down – the resultant pressure waves may cancel each other out, so that what reaches the audience is a summation of the survivors. The violinist's ear, however, is in a privileged position. It is bathed in sounds, not all of which reach the audience. This is one reason why it is difficult for violinists to judge projection reliably simply by playing an instrument. Loos's experiments demonstrate that there is no need to go to the back of the hall to assess this particular aspect of projection; one need only step back a few feet.

It is interesting to follow the progress of the sound waves as they move away from the violin. In an open space, or an acoustically dead room, sound pressure decreases with the square of the distance – a very rapid diminution. This is the Inverse Square Law and is easily understood if one thinks of a sound wave as the surface of a rapidly expanding sphere. The wave's initial energy is spread more and more thinly as the sphere's surface area grows larger. The surface area of a sphere is proportional to the square of its radius, so the sound pressure falls inversely to the square of that radius – the radius in this case representing the distance between listener and violin. If our ears translated sound pressure directly into a subjective sense of loudness, the instrument would very soon become inaudible. Fortunately, our sense of loudness is governed by the opposite relationship; it is roughly proportional to the square root of the sound pressure. The square and the square root cancel each other out, so we can say that, in an open space, loudness decreases more or less proportionally with distance.

Do these relationships hold for a more traditional listening environment, such as a concert hall? If loudness decreased proportionally with distance, in Loos's experiment the loudness at twelve metres would be about one twelfth ▸

Measuring sound levels

A sound-level meter (right) measures the tiny, rapid fluctuations in atmospheric pressure we hear as sound. Our ears function over an enormous range of sound pressures; in very quiet settings we can hear the drumming of air molecules against our eardrums, while the highest sound pressures we can tolerate without damage to the ear are about one billion times greater. Sound pressure is measured in pascals (Pa), a measure of force per unit area. In order to compress the ear's huge range into a manageable notation, we use Sound Pressure Level (SPL), which is measured in decibels (dB) and represents a logarithmic ratio of the measured sound pressure to the smallest audible pressure of 0.00002Pa. Under the ear, a violin can easily reach 100dB. To put this in perspective, the threshold of pain arrives (with a further ten-fold increase in sound pressure) at about 120dB. Instant perforation of the ear drum occurs at 160dB.

Photos: top: Royal Festival Hall; bottom: Extech

of its value at one. She found it to be half. Why? Because the reverberance of the hall bolsters the sound level by effectively trapping sound that would otherwise be lost in space. Here's an interesting experiment: take a sound-level meter and walk slowly away from a steady sound source, such as an electronic tuner set to A440. The needle falls steadily at first. Then at a certain distance from the source it stops falling and stays about the same, no matter how far back one goes. And this is true in any concert hall, no matter how large.

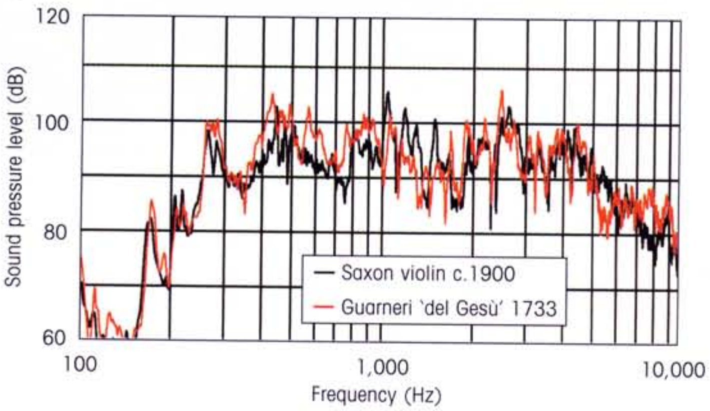
The reason is that the sound pressure at any point in the hall is made up of two components: sound arriving directly from the source and sound arriving indirectly by way of reflection from the surfaces of the room and the fittings. The reflected sound bounces around the hall from surface to surface until it is absorbed, and in doing so fills the hall with a kind of vibrational soup whose recipe depends on the particular acoustics of the hall. Direct sound from the violinist is mixed into this soup, which is, of course, a mish-mash of sounds that the violinist made slightly earlier. As you move away from the violinist, the direct sound becomes weaker until at some point it equals the indirect sound. Depending on a concert hall's particular volume, this typically happens at about ten metres. Beyond this critical radius, it doesn't really matter where you sit, at least in terms of the overall sound level. This doesn't mean that the closer seats are not worth the extra money but you are paying for the clarity rather than volume, because the further away you sit, the lower the ratio of direct to indirect sound. Since the critical radius is smaller in more reverberant halls, a good seat is especially important in very reverberant spaces such as churches.

The surfaces in a normal concert environment usually absorb high frequencies more readily than low frequencies, so the indirect, reflected sound tends to have a low-frequency emphasis. A violin that radiates well at high frequencies therefore has an advantage when it comes to clarity; its high harmonics tend to be less muddied by the room reflections. And good high-frequency radiation, we shall see, is crucial to projection for several other reasons.

Loos also investigated the distribution of the sound radiation across the frequency range of each of the violins (a similar comparison can be seen in figure 1). The violins that delivered strong lower harmonics were found to project well – these harmonics lending the instrument a sense of proximity. This suggests another aspect of projection: the ability to close the distance between player and listener. As the violinist Erick Friedman once remarked, 'I want an instrument that has an intimate sound. Fifty feet away.' Further experiments found that the levels of the high harmonics made no special contribution to projection. This comes as a surprise, at least to researchers: prevailing theories attribute projection to precisely these higher harmonics, in particular those which fall in the ear's most sensitive region, around 3,000Hz. This paradox is surely one of context – Loos was comparing violins played solo in an otherwise quiet hall. Violinists frequently do the same while shopping for an instrument, so the question becomes: 'Do judgements made in this context hold ▸

WHEN IT COMES TO CLARITY, A VIOLIN THAT RADIATES WELL AT HIGH FREQUENCIES HAS AN ADVANTAGE IN A CONCERT-HALL ENVIRONMENT

Figure 1



How do violins differ in the sound they produce? The black line illustrates the amount of sound produced by an inexpensive Saxon violin, across its frequency range, for a given force on the bridge. The red line displays the same data for a 1733 Guarneri 'del Gesù'. Compared to the Saxon, the peaks of major resonances of the Guarneri are often 6dB higher and the overall power is approximately 1.5dB greater. As we shall see in the next article, good contemporary instruments can deliver sound levels in the range of the Guarneri. The difficult thing is matching the proportions of sound in the different frequency regions. Quality is less a question of absolute power than the distribution and balance of energy. The Saxon violin is very strong in the unpleasant nasal area (1,000–1,800Hz), while the Guarneri clearly dominates in other regions.

Figure 2

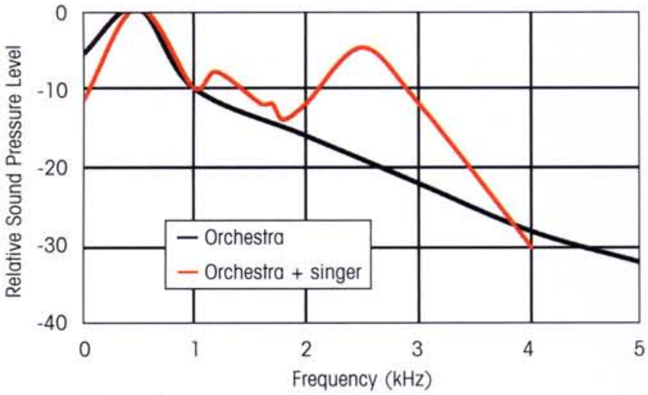
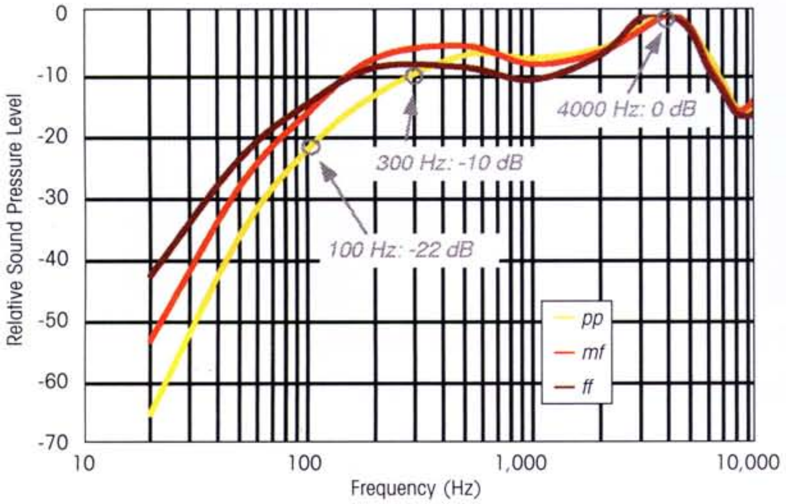


Figure 3



ABOVE the ear's sensitivity to sound varies across its frequency range. Each curve in figure 3 displays a constant perceived loudness – *pp*, *mf*, or *ff*

THE ABILITY TO PRODUCE SOUND AT AROUND 3,000HZ CAN DETERMINE WHETHER A VIOLIN WILL SUCCEED OR FAIL AS A SOLO INSTRUMENT

up when the competition arrives?' After all, being heard in a large hall over a full orchestra goes to the heart of what most violinists mean by projection.

If we think of the concert hall as a kind of Darwinian jungle with a wide variety of instruments competing for attention, then we find that orchestral instruments have adopted a variety of strategies for making themselves heard: basses occupy a low-frequency range where there is little competition from other instruments; the drum concentrates a large amount of energy into very short bursts; the trumpet simply puts out a great deal of sound. In this regard, the violin is at a disadvantage and often takes refuge in numbers. But the violin's success as a solo instrument suggests it has other ways of holding the audience's attention.

In the 1970s the Swedish acoustician Johann Sundberg studied recordings of the famous tenor Jussi Bjoerling and found that the average frequency spectrum of his voice had a large 'hump' at around 3,000Hz, especially when Bjoerling was singing with orchestral accompaniment. This hump is known as the singer's formant – a formant is a concentration of energy in a particular frequency range.

Figure 2 plots the average loudness spectrum of an orchestra with (red) and without (black) a singer. Clearly, a large proportion of this is concentrated below 1,000Hz. Figure 3 shows that the sensitivity of the human ear peaks at about 3,000Hz, especially at low listening levels, and it is a peculiarity of the ear that a sound in one frequency region will not be masked by sounds in another. Most researchers agree that when it comes to large halls and competitive musical contexts, an ability to produce sound in the 3,000Hz region determines, to a great extent, whether a violin will succeed or fail as a solo instrument. Loos's work suggests there is a second model for projection, relying on strong low harmonics. In the next part of this series we shall see that old Italian violins are unusually adept at producing sound in both these important frequency regions, thus satisfying both models.

Sizzle

Electronic amplifiers strive for a perfectly flat frequency response. Violins, by contrast, present a Himalayan landscape of peaks and valleys, each peak representing a point of maximum sound radiation. This has profound effects on the instrument's tone, the special quality of violin vibrato being a good example. As the pitch of a note changes slightly, different harmonics ride different slopes of the violin's jagged response curve. At any one instant, one harmonic might be ascending, and so increasing in amplitude, while a second descends. Higher overtones may even cross several peaks and valleys in a single vibrato cycle. This amplitude modulation of harmonics lends the tone a characteristically violin-like liveliness, a kind of texture one might call a sizzle. Our senses are highly adapted to detecting changes in the environment; things that remain constant tend to be ignored. Vibrato introduces an element of constant change, making each note more noticeable, and the amplitude modulation of harmonics only heightens this effect. Is this a component of projection? We would instinctively say 'yes', but more research is needed.