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Scientific measurements of sound generation and radiation by musical instruments are surprisingly hard to correlate with the subtle and complex judgments of instrumental quality made by expert musicians.

Even in the womb, unborn children hear and respond to music; and throughout life, music accompanies and enriches many of our most significant activities. From ancient times, philosophers and scientists have studied the nature of musical sounds and the instruments that generate them. To a physicist, there is a fascination in exploring how to apply the relatively simple laws of classical physics to obtain a detailed description of the complex and rapidly varying sound fields produced by performers and transmitted through a concert hall to the listeners. Many of the musically important aspects of sound production in instruments involve subtle features of the underlying physics, and those subtleties can reveal the limitations that arise from simplifications and approximations in physical models of the instruments.

Beyond the general appeal of physical understanding, another important motivation behind current research into the physics of musical instruments is the desire to offer helpful guidance to instrument designers and manufacturers. Traditionally, those craftsmen have used techniques and rules of thumb developed over generations by trial and error; the aim of many scientists working to understand musical instruments is to supplement such hard-won empirical knowledge with scientific principles and useful tools that will enable excellent instruments to be built in a more reliable and cost-effective way. Although considerable progress has been made in recent decades, the goal remains unexpectedly elusive. One reason is that achieving a highly accurate physical model of any musical instrument is a significant technical challenge: Details are still not fully understood, for example, of the frictional processes in the bow–string interaction in a violin or of the fluid–structure interaction driving an oboe reed.

A more profound problem lies in the definition of the very nature of the goal: If we are to optimize a musical instrument, who determines success? Ultimately, of course, it must be the musician who will play the instrument or the listener who will hear its sound. The problem is that musicians and physicists usually approach the evaluation of the quality of an instrument in very different ways, and they

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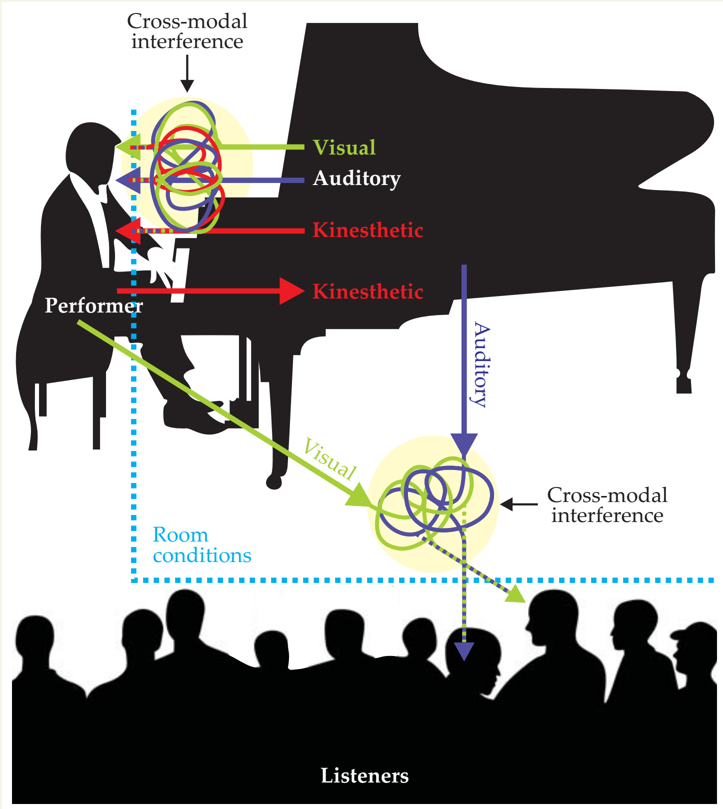


Figure 1. A pianist creates and modifies a musical performance in response to information received through three senses: hearing (the auditory channel), sight (the visual channel), and touch (the kinesthetic channel). The player's perception of the tonal quality of the piano sound can be biased by the other senses, so-called cross-modal interference from visual and kinesthetic cues, depicted here as a tangled input. A listener's perception of the sound quality can likewise depend on the appearance of the instrument, the player, and even the hall. (Adapted from ref. 4.)

frequently lack a common vocabulary in which to discuss their differences.

Early studies of musical instrument quality concentrated on the frequency spectra of the steady-state parts of the radiated sound and ignored the complicated transients at the beginning and end of notes. Later it became clear that such transients were not only critical cues for the identification of particular instruments but also important aspects of what musicians describe as "timbre" or "tone color"—the quality of sound that distinguishes a note played on a clarinet from a note of the same pitch and loudness played on a trumpet. In more recent years, scientific attention has increasingly turned toward the interaction between player and instrument and has recognized that "playability"—a measure of how well the player can evoke the desired response from the instrument—is a key attribute for a performer.

The task for the musical instrument acoustician is thus to establish the objectively measurable properties of a given instrument that correspond strongly to timbre perception and playability as judged by musicians, and then to propose methods by which those properties can be optimized. Such an approach has been used in studies of pianos, violins, brass, and other musical instruments.

A further problem emerged from such studies. The interaction of the player with an instrument involves several senses: Sight, hearing, touch, and even smell can contribute to the player's experience, and those different sensations can become confused in judgments of quality. The possibilities of such "cross-modal interference" must be understood and minimized. Only then can player judgments be considered sufficiently robust to correlate with scientifically measured data. Let's look at three examples.

What makes an excellent piano?

At first glance, the piano might seem to be one of the simplest musical instruments to model scientifically. When the performer presses a key, a hammer pivoted at one end is thrown toward a string, as shown in the opening figure; the escapement mechanism ensures that the hammer head rebounds from the string after striking it, and a check then holds the hammer to prevent multiple strikes. The vibrations of the string are communicated through a bridge to the wooden soundboard, which vibrates and radiates sound into the room.

The simplicity is deceptive: Many aspects of the piano must be modeled with great care to give a realistic sound output.[1] Because the hammer's head is covered by several layers of felt with nonlinear compressive behavior, the spectral distribution of the energy communicated to the string is strongly dependent on the hammer's impact velocity. The finite stiffness of the steel piano string results in a significant inharmonicity of the natural transverse vibrational modes of the string, which affects both the timbre of the radiated sound and the overall tuning of the instrument (see box 1). The soundboard's resonant frequencies, radiation efficiencies, and damping parameters are influenced by its size, shape, and bracing. Upright pianos typically have smaller soundboards and shorter bass strings than grand pianos, which are preferred by most performers. The fact that inharmonicity is less for a long string than for a shorter string at the same pitch is sometimes cited as the reason for that preference, but careful studies by Alexander Galembo suggest that the influence of the larger soundboard on the spectral envelope of notes in the bass register is the main reason.[2]

Over most of the piano's compass, three strings are struck simultaneously when a key is pressed. Musicians describe them as "unison" strings. Interestingly, however, precise measurements of grand-piano strings after expert tuning reveal that typically there are pitch differences of about 1.5 cents (1.5% of a musical semitone) between the strings. Gabriel Weinreich has shown that such mistunings can encourage mode locking between the strings,[3] reducing the rate at which energy is transferred from the strings to the soundboard. Consciously or unconsciously, the master tuners are enhancing the singing quality associated with a slow decay of the piano sound by introducing subtle deviations from the nominal target of unison tuning.

Some pianists believe that by merely altering the manner in which the key is depressed, it is possible to change the timbre of a single note, without altering its loudness. It is hard to see how that can be true, since the only variable affecting the nature of the string vibration is the speed of the hammer at impact. The player has no direct contact with the strings and relies on the key mechanism (supplemented by judicious use of the sostenuto and una corda pedals) to create and control an expressive musical performance. But haptic—which includes feedback from both muscles and pressure receptors in the skin—and auditory piano cues can become entangled: For example, the tiny sound made by a finger contacting the key surface may be more salient to the player because it is accompanied by the sensation of touch in the fingertip.

The extent to which cross-modal interference can influence judgments of quality by pianists was revealed in a series of experiments carried out in the 1970s in the Leningrad Conservatory concert hall.[4] Twelve professional pianists were asked to rank three grand pianos, including a Steinway and an instrument made by the Leningrad piano factory, on scales of tone quality, dynamic range, and playing comfort. When allowed to make a judgment based on free playing, the pianists agreed that the Steinway was distinctly superior in tone quality to the other pianos. However, when sample single notes, scales, and arpeggios were played for them behind an acoustically transparent curtain, the same pianists were unable to reliably identify which instrument was being played.

In another experiment, the three pianos were placed so that the keyboards formed a triangle with a rotating piano stool at the center. Pianists were each blindfolded to suppress visual cues, and presented with the pianos in random order; they were able to identify the instruments with a high degree of accuracy. The sound was then suppressed by using white-noise headphones; surprisingly, even to the subjects, the sight- and hearing-impaired players were still able to correctly identify the instruments. Apparently, the discriminating factor was contained not in the auditory signal but in the haptic sensations, which contained information about the mechanical actions of the instruments. The players perceived the sensations as differences in tone quality because of cross-modal interference between auditory and haptic (kinesthetic) channels (see figure 1).

Box 1. Inharmonicity and octave stretching

An idealized flexible stretched string, fixed rigidly at both ends, provides a classic textbook case of a vibrating system with a set of harmonically related modes.[14] The second mode has twice the frequency of the first, and the pitch interval between the two modes is an octave. The two statements in the previous sentence are generally considered to be equivalent, the term "octave" defining a frequency ratio of exactly 2. Yet that is not quite right. The finite stiffness of the steel wire used in piano strings introduces a small but significant inharmonicity in the string modes: In the middle of the piano keyboard, the frequency ratio of the first two modes is typically around 2.001, and the degree of inharmonicity increases with mode number. Since the modes decay freely after the hammer head has rebounded from the string, the frequency components of the radiated sound are also inharmonic.

In the traditional method of piano tuning, octaves are regulated by minimizing beats between the first frequency component of the upper note and the second frequency component of the lower note. The inharmonicity of those components leads to "octave stretching": The pitch interval between the fundamental frequencies of the notes A0 and A7 on a well-tuned piano is typically around half a semitone greater than it would be if each of the seven octaves involved had a frequency ratio of exactly 2. While a high degree of inharmonicity in piano strings is undesirable, experiments in synthesizing piano sounds[15] have revealed that the level of inharmonicity found in good-quality grand pianos and the associated degree of octave stretching are considered by musicians to be essential features of the sound of the instrument. (For a tale of Richard Feynman's encounter with piano tuning, see PHYSICS TODAY, December 2009, page 46; relevant letters followed in June 2010, page 8.)

Have we lost Stradivari's secret?

The evaluation of musical instrument quality has an unusual financial significance in the case of the violin. Instruments made around three centuries ago by Antonio Stradivari and Giuseppe Guarneri "del Gesù" now command prices two orders of magnitude greater than those charged by the best modern violin makers. Although various nonmusical factors are involved in such a gross disparity in price, many players believe that violins made by the old Italian masters have special qualities that cannot be found in modern instruments. Numerous attempts to discover a supposedly lost "secret of Stradivarius," perhaps in the choice of wood or the chemical composition of the varnish, have all been inconclusive.

The acoustical quality of a violin is closely linked to its structural resonances.[5] The violin body is in essence a hollow box whose top plate is pierced by two f-shaped holes. When a string is bowed, frictional stick–slip interactions generate an oscillating force with a sawtooth waveform that is transmitted to a thin wooden bridge sitting on the top plate between the f-holes; the bridge's motion communicates the vibration to the body, which radiates the sound. Various researchers, notably Erik Jansson at KTH in Stockholm[6] and Jim Woodhouse at the University of Cambridge,[7] have studied violin body resonances by measuring the bridge admittance, defined as the ratio of the bridge velocity to the force applied to the bridge. In Woodhouse's technique, illustrated in figure 2a, an impulsive force is applied by a small pendulum hammer carrying an accelerometer, and the resulting bridge velocity is measured with a laser vibrometer.

A typical bridge-admittance curve for a good-quality modern violin is shown in figure 2b. At first sight it may seem surprising that the response is so uneven—the drop of 30 dB between 550 Hz and 700 Hz is particularly striking. Yet that feature is characteristic of high-quality instruments, old and new, as are the group of discrete "signature modes" between 200 Hz and 600 Hz and the "bridge hill" of closely spaced and overlapping modes between 1500 Hz and 3000 Hz.

A consequence of that nonuniformity of response

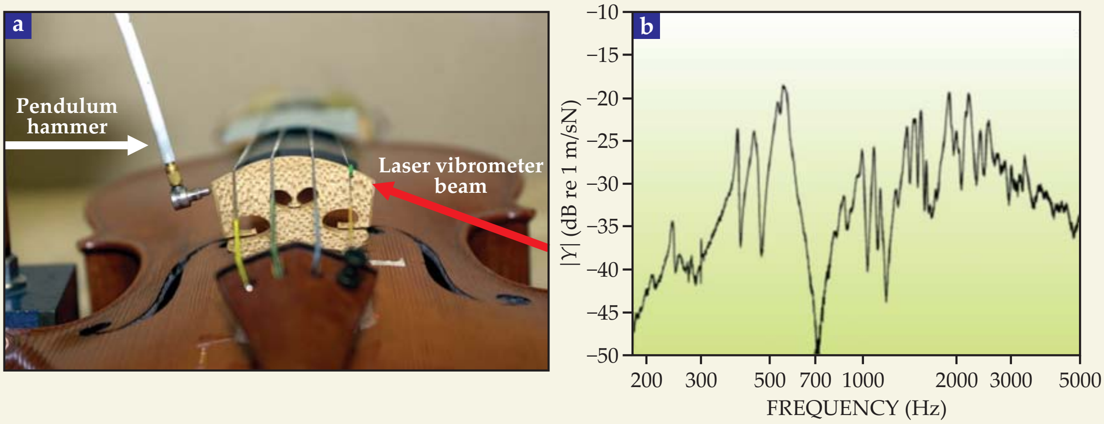


Figure 2. A measurement of the bridge admittance of a violin **(a)**. The strings are damped, and a light pendulum hammer whose head carries a force transducer taps one of the upper corners of the violin bridge. A laser vibrometer measures the bridge velocity at the other upper corner by recording the Doppler shift in the reflected laser beam. After appropriate calibrations, the frequency dependence of the bridge admittance *Y* is given by the complex ratio of the vibrometer and force-transducer signals. The bridge-admittance curve **(b)** for a typical high-quality violin is surprisingly complex. (Figures courtesy of Jim Woodhouse.)

is that the timbre of a note will depend strongly on its pitch. For the note G3—the G below middle C, with a frequency of about 196 Hz—the first harmonic of the bridge force will evoke a body response around 20 dB lower than the second harmonic at 392 Hz; for the note F4 at 349 Hz, the response at that first harmonic will be around 20 dB higher than at its second harmonic frequency of 698 Hz. The spectral differences are further modified by differences in the radiating efficiency of body modes, but such pitch-dependent timbral changes are characteristic features of violin sound and are considered essential aspects of the instrument's character by players and listeners alike.

Are there features of a bridge-admittance curve, such as specific frequencies of signature modes, that can be used to identify an excellent instrument? Is it even possible that this type of analysis could reveal the "acoustic fingerprint" of Stradivari? Those questions are clearly of great interest to modern makers, but intensive research over the past five decades has failed to yield definitive answers. A 2008 review by George Bissinger of East Carolina University concluded that the only features to distinguish violins of the highest quality are a relatively uniform spread of resonances and a relatively strong response in the lowest frequency band around 280 Hz.[8]

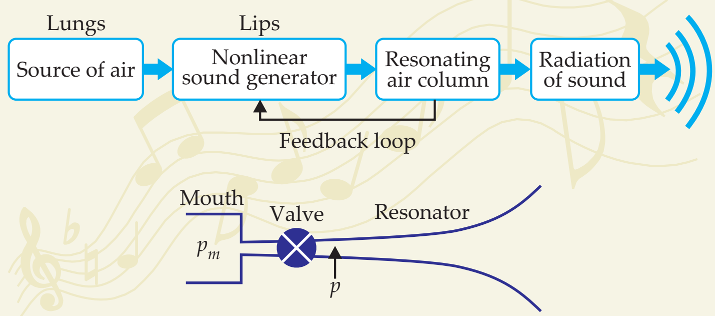


Figure 3. A note on a brass instrument begins when a player increases the mouth pressure p_m. The lips act as a pressure-controlled flow valve: The relationship between the pressure difference across that valve and the airflow through it is nonlinear, and when the pressure difference reaches a critical threshold, a self-sustained oscillation of the lips occurs. If the lip frequency is close to one of the resonant frequencies of the air column within the instrument, a strong standing wave builds up in the tube, creating an oscillating pressure p at the mouthpiece, which helps to stabilize the lip vibration.

To make further progress in finding objective measures of violin quality, we must improve our understanding of the nature and reliability of the judgments made by professional violinists. In 2012 Claudia Fritz and colleagues published the results of an important experiment in which 21 experienced violinists were asked to evaluate and compare six violins.[9] Three of the instruments were made by Stradivari or Guarneri, and the remaining three were by highly regarded contemporary makers. The players were allowed to make their judgments on the basis of free playing in a hotel room that was acoustically dry—having short reverberation times. The illumination level was low and the players wore goggles to avoid cross-modal interference from visual identification of the instruments. The players rated the playability, response, and tone color of the instruments on the basis of auditory and tactile information.

Although it has often been claimed that an expert player can immediately distinguish an antique violin from a new one, the musicians in the experiment were unable to make the distinction at a level greater than chance. Overall, the new violins were rated more highly for playability and response than the old Italian instruments; no significant distinction was made between old and new instruments on the basis of tone color. Those findings have been confirmed by a further experiment using a larger number of violins.

The work by Fritz and her colleagues suggests strongly that when distracting visual cues and prior expectations are suppressed, expert players judge the best modern instruments to have a level of quality at least as great as the classic instruments made by the old Italian masters. The remaining scientific challenge is to identify which aspects of the physics of the violin are responsible for the performance of an instrument, whether old or new, that is judged to be excellent by an internationally renowned performer.

Must brass instruments be made of brass?

Trumpets, trombones, and tubas are known as brass instruments and are commonly made from the metal alloy known as brass. The dominant acoustical characteristic of the musical brass family is not the material of construction, however, but the method by which the sound is generated: the vibration of the player's lips, usually pressed against a cup- or funnel-shaped mouthpiece.[10] (Saxophones are also generally made from brass, but because the mouthpiece holds a reed, they are considered woodwind instruments.)

The relationship between the player and the instrument is illustrated in figure 3. Air from the player's lungs flows past the lips and into the instrument. The air column bounded by the wall of the instrument can be treated to a first approximation as a passive linear system, whose resonant properties are described by the input impedance (the ratio, at the mouthpiece input plane, of acoustic pressure to the oscillating volume velocity of the air flow that produced it). When a note is sounded, the player's lips open and close at the frequency of the played note. An oscillation regime builds up in which the modulated airflow supplies energy to the acoustic resonances of the air column; the resulting pressure variation in the mouthpiece provides feedback that stabilizes the lip vibration.

Although the variation of the open area between the lips is approximately sinusoidal, the nonlinear nature of the pressure-flow relationship results in pressure variations within the mouthpiece at harmonic multiples of the basic lip oscillation frequency. When the acoustic resonances of the air column also occur at harmonic multiples of that frequency, a strong oscillation regime is established. The player's perception is of a "well-centered" note: The playing frequency is clearly defined and stable. Harmonic alignment of the acoustic resonances is therefore usually considered to be a measure of high quality in brass instruments.

Subtle modification of intonation is, however, an important feature of expert musical performance, and brass players frequently "bend" or "lip" a note by small adjustments of the facial muscles that control the mechanical resonance frequency of the lips. Judgments of the playability of brass instruments involve a balance between strongly centered pitches and flexibility of intonation; the relationship between those properties and measured input-impedance curves requires further investigation.

One of the most striking features of the sound of a trumpet or trombone is the way in which the timbre changes during a crescendo. When a trumpet is played quietly, the frequency spectrum of the sound is dominated by the first four or five harmonics; as the loudness increases, the spectrum becomes increasingly rich in upper harmonics. At the fortissimo level, a particularly hard and brilliant timbre is generated; such sounds are described by musicians as "brassy," reflecting a common assumption that the effect arises from structural resonances of the metal bell of the instrument (also see box 2). Although the spectral enrichment in very loud playing is now known to arise primarily from nonlinear sound propagation in the instrument's air column,[11] many makers and players continue to insist that the wall material of a "brass" instrument is important in determining the musical quality of the instrument's sound.

Some 30 years ago, acoustician and brass instrument maker Richard Smith investigated the reliability of players' judgments of brass instrument quality.[12] Ten professional trombonists were asked to play and evaluate a number of tenor trombones with brass bells of different wall thickness. All the bells were made on the same mandrel to ensure that they had the same internal dimensions, and the mass distributions of the instruments were equalized. Visual cues were eliminated by blindfolding the players. Under those circumstances the players could not distinguish between the instruments. A pure copper bell included in the test set was not identified as having a noticeably different timbre, yet Smith reported that "when subsequently played in non-blind tests it gained magical properties!" That classic experiment provides yet another example of the way in which quality judgments by players can be biased by cross-modal interference.

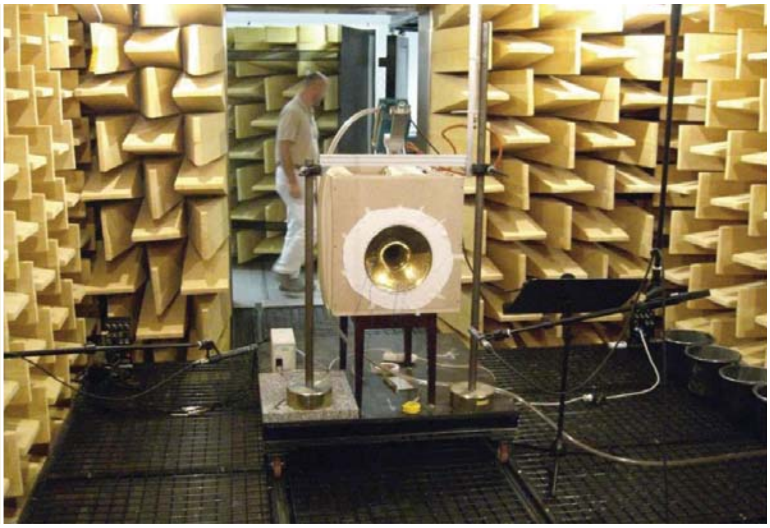
The question of the extent to which wall vibrations contribute to the sound radiated by brass

Box 2. Shock waves in trombones

When a trombone is played loudly, the amplitude of the internal pressure wave can exceed 10 kPa. At that level, linear acoustics is inadequate to describe the wave propagation, since the local speed of sound becomes dependent on pressure. The crest of the pressure wave travels faster than the trough, which results in a progressive steepening of the wavefront. At a critical distance along the tube—a distance that depends on the rate of change of the pressure signal in the mouthpiece and the bore profile of the instrument—the almost instantaneous pressure jump characteristic of a shock wave appears.

The sound radiated from the trombone's bell when an internal shock wave is created has a very wide spectrum of harmonics that can extend well into the ultrasonic range. Even at moderate playing levels well below the threshold for shock formation, distortion arising from nonlinear sound propagation can make a significant contribution to the timbral palette of the brass player. Instruments with an approximately conical bore, like the cornet and the euphonium, are less susceptible to nonlinear distortion than instruments with long sections of cylindrical tubing, such as the trumpet and trombone. That is because the progressive increase in the cross-sectional area of the wavefront propagating in a conical tube corresponds to a reduction in the pressure amplitude. Studies of nonlinear propagation effects have led to increased awareness of the scientific reasons for some of the subtle differences in timbre and playability among instruments of the brass family.[16]

Figure 4. The experimental arrangement used at the Institute of Musical Acoustics (IWK) in Vienna to investigate the influence of wall vibrations on the sound radiated by a French horn. The instrument was mounted in a wooden box, which could be filled with sand to damp the wall vibrations. The horn was driven by an artificial mouth with water-filled rubber lips, and the sound from the bell was radiated into an anechoic chamber through a circular aperture in the front wall of the box. Significant changes in the spectral content of the radiated sound were measured when the walls were damped; that confirmed similar findings in studies of a trumpet by Thomas Moore and colleagues at Rollins College. (Image courtesy of Wilfried Kausel.)



instruments remains controversial. In experiments with a mechanical sound source, Smith measured the sound output from the trombones used in his blind tests. He found that differences of several decibels in specific frequency components, measured at a position corresponding to the left ear of a human player, were correlated with changes in the wall thickness of the bell. The differences were not, apparently, recognized by the players in the blind tests.

Recently Wilfried Kausel, Daniel Zietlow, and Thomas Moore have undertaken systematic studies of wall-vibration effects in brass instruments,[13] using an artificial lip excitation source and an experimental arrangement that allows the wall vibrations to be damped by sand (figure 4). They found that damping the wall vibrations resulted in several-decibel increases in the first few harmonics of the radiated sound, along with reductions in the amplitudes of higher harmonics. Further blind tests using professional performers will be necessary to clarify the importance of wall vibrations in musical practice.

Science and music: A dialog

The scientific understanding of the functioning of musical instruments has progressed notably in the past few decades, aided by the growing sophistication of both acoustical measuring instrumentation and computational simulation techniques. It is increasingly evident, however, that the transfer of scientific knowledge from the research community to musical instrument makers and performers relies on relationships of mutual respect between creative musicians and those who seek to study them scientifically. Musicians sometimes look with scorn on simplified models that physicists use to explore the fundamental principles of an instrument's behavior. Scientists need to explain that the models are steps along a route that could ultimately lead to insights of great value to a maker or player. On the other side, scientists can be dismissive of performers whose evaluations of instruments are biased and inconsistent, but it is essential to remember that it is the performer who brings the instrument to musical life and who must be the ultimate arbiter of its quality.

Fortunately, there are now several international forums in which scientific researchers, performers, and makers come together regularly to discuss such problems in an open and constructive way. One important and very productive forum at which stringed instrument makers and researchers get together is the annual Acoustics Workshop organized jointly by the Violin Society of America and Oberlin College (http://www.vsa.to/oberlin-workshops). The International Symposium on Musical Acoustics takes place every two years (this summer in Le Mans, France: http://isma.univ-lemans.fr), usually involving both practical workshops and academic sessions. The Institute of Musical Acoustics at the University of Music and Performing Arts Vienna periodically organizes meetings designed to bridge the gap between scientists and makers (http://viennatalk.mdw.ac.at/); the next meeting will be in 2015. Such dialogs should lead to a deeper understanding of the mysterious but fascinating relationships between scientific and musical evaluations of the quality of musical instruments.

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