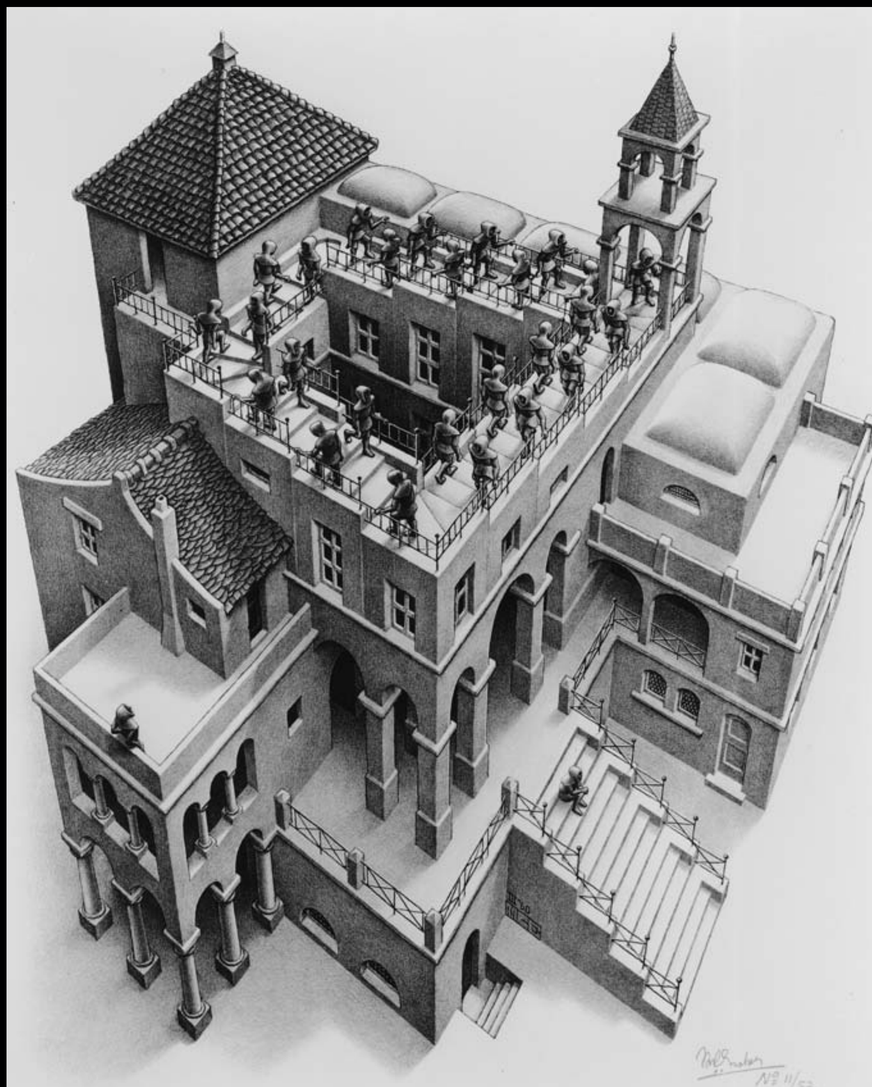
VOLUME 6, ISSUE 3 JULY 2010

Acoustics Today



Pitch Circularity
The Musician's Auditory World
Musical Disorders and Stroke Recovery
Banjo Modeling
Acoustical Society's Jam
and more

A publication of the Acoustical Society of America

The Music Issue

Acoustical Society of America

PROCEEDINGS OF MEETINGS ON ACOUSTICS

ASA’s meetings proceedings publication

Open access	No author fees
Flexible format	Rapid publication

Authors of papers submitted for presentation at the Portland meeting are invited to submit written versions of their papers to the Acoustical Society of America's new archival serial publication, *"Proceedings of Meetings on Acoustics" (POMA).*

Each article in POMA corresponds to a paper that has been presented at a meeting of the Society. It is open-access, so all articles can be viewed without charge by anyone with the capability of down- loading material from the internet.

Each article will be reviewed by an Associate Editor, each of whom represents a Technical Committee of the Society.

Format requirements for manuscripts submitted to POMA are very flexible, with the desire that authors will not have to spend too much time in the actual preparation of their manuscripts. It is required that you include no previously copyrighted material in your paper unless you have explicit permission to do so.

Submission guidelines are found at

http://asa.aip.org/poma.html

Articles pubilshed in POMA are found at

http://scitation.aip.org/POMA

ACOUSTICAL SOCIETY OF AMERICA

The *Acoustical Society of America* was founded in 1929 to increase and diffuse the knowledge of acoustics and to promote its practical application. Any person or corporation interested in acoustics is eligible for membership in the Society. Further information concerning membership, as well as application forms, may be obtained by addressing Elaine Moran, ASA Office Manager, Acoustical Society of America, Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502, Telephone (516) 576-2360; Fax: 516-576-2377; E-mail: asa@aip.org; Web: http://asa.aip.org

FUTURE ARTICLES

3-D Sound

Acoustic Diversity

Noisy Planet

Acoustics Internet Outreach

Feedback in Sound Design

3-D Imaging

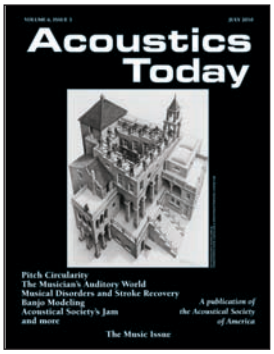
Bow Bells

ACOUSTICS TODAY (ISSN 1557-0215, coden ATCODK) July 2010, volume 6, issue 3 is published quarterly by the Acoustical Society of America, Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502. Periodicals Postage rates are paid at Huntington Station, NY, and additional mailing offices. POSTMASTER: Send address changes to Acoustics Today, Acoustical Society of America, Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502.

Acoustics Today

A Publication of the Acoustical Society of America

Volume 6, Issue 3 **July 2010**



Cover: In viewing M. C. Escher's lithograph *Ascending and Descending* shown on the front cover, we see monks plodding up and down an endless staircase—each monk will ultimately arrive at the place where he began his impossible journey. Our perceptual system insists on this interpretation, even though we know it to be incorrect.

7 **From the Editor and the Guest Editor**

Articles:

8 **The Paradox of Pitch Circularity**—*Diana Deutsch*
Scales and glides that appear to ascend or descend endlessly in pitch have long been a source of fascination for scientists and musicians alike.

15 **The Musician's Auditory World**—*Nina Kraus and Trent Nicol*
The auditory system is at the center of the world of communication, and a finely tuned auditory system extends to many uniquely human endeavors such as language, speech and interpretation of emotion.

28 **Neurological Bases of Musical Disorders and Their Implications for Stroke Recovery**—*Psyche Loui, Catherine Y. Wan, and Gottfried Schlaug*
How does the understanding of tone-deafness help patients recover from stroke?

37 **The Banjo: The "Model" Instrument**—*Joe Dickey*
Why do we do this? Partly to build better banjos or help people who fix or play banjos get a better sound by understanding how the various components of the instrument work together and influence the sound.

42 **The Society: In a Jam, and Loving It**—*K. Anthony (Tony) Hoover*
The ASA Jam—Tasty and Sweet

Departments:

45 **Acoustical News—***Elaine Moran*
Acoustical news from around the country and around the world.

50 **Books and Publications—***Dick Stern*
New and recent reports, publications, and brochures on acoustics.

Business Directory

51 Business card advertisements

52 **Index to Advertisers**

FROM THE EDITOR

Dick Stern
Applied Research Laboratory, The Pennsylvania State University
PO Box 30, State College, Pennsylvania 16804

It was both an honor and privilege to work with Diana Deutsch, the guest editor for the editorial content of this issue of *Acoustics Today*—the Music Issue. In addition to writing an excellent article on pitch circularity, her ability to select the authors and the research material to be included made it easy for me to edit one of the largest issues of the magazine.

I invite others to think about becoming a guest editor for a theme issue of their choosing and to e-mail me at AcousticsToday@aip.org with their ideas.

(Note Editor at the Portland Jam Session.)

I hope to see everyone in Cancun

Dick Stern

FROM THE GUEST EDITOR

Diana Deutsch
Department of Psychology, University of California, San Diego
La Jolla, California 92093

This special issue of *Acoustics Today* is devoted to music. It explores recent advances in the study of music from four perspectives, and illustrates the diversity of questions that are addressed in this area of research. The issue includes, among other things, an exploration of pitch circularity, discussions of the relationships between music and language, examination of the function of the auditory brainstem, music as a tool in promoting recovery from stroke, and physical modeling of instrument sounds.

In *The Paradox of Pitch Circularity*, I explore illusions that involve a series of tones that ascend or descend endlessly in pitch. The paper focuses on a new algorithm for producing pitch circularity with sequences of single tones each of which forms a full harmonic series. This algorithm can in principle be employed to transform banks of natural instrument tones so that they acquire circular properties. In addition to its implications for theories of pitch perception, this algorithm opens up new avenues for music composition and performance.

Nina Kraus and Trent Nicol, in *Musicians' Auditory World*, discuss findings on musical training and its effects on other functions. The authors show that musical training strengthens auditory memory and attention, and they argue that this in turn leads to improvements in phonological processing, reading, and the extraction of speech from background noise. The article focuses on findings on the non-invasive brainstem response, which can be remarkably stable and faithful to the signal sent to the ear.

Psyche Loui, Catherine Wan, and Gottfried Schlaug, in *Neurological Bases of Musical Disorders and Their Implications for Stroke Recovery* explore behavioral and neuroscience studies on singing; these include the investigation of trained singers, as well as tone-deaf individuals who have difficulty singing. They examine the neuroanatomical bases of expert singing and tone deafness, in the latter case considering possible links with certain speech disorders. They also discuss therapeutic effects of singing in facilitating recovery of language functions in patients who have suffered brain damage.

Joe Dickey, in *The Banjo: The 'Model' Instrument* presents us with an article on analytical modeling of the behavior of the plucked banjo. This article is accompanied by numerous illustrations, and three time-evolution movies, and it demonstrates engagingly why modeling the behavior of musical instruments can be so rewarding.

Finally, many members of the ASA play musical instruments, but until recently our meetings have only rarely afforded us the opportunity to participate actively in musical events. In *The Society: In a Jam, and Loving It*, Tony Hoover presents a brief history of the highly welcome new tradition of holding Jam sessions at our meetings. These began at the 2007 New Orleans meeting, and are well and enthusiastically attended—we look forward to many more.

THE PARADOX OF PITCH CIRCULARITY

Diana Deutsch
Department of Psychology, University of California, San Diego
La Jolla, California 92093

Introduction

In viewing M. C. Escher's lithograph *Ascending and Descending* shown on the front cover, we see monks plodding up and down an endless staircase—each monk will ultimately arrive at the place where he began his impossible journey. Our perceptual system insists on this interpretation, even though we know it to be incorrect. The lithograph was inspired by the endless staircase devised by Lionel Penrose and his son Roger Penrose,[1] a variant of which is shown in Fig. 1. Our visual system opts for a simple interpretation based on local relationships within the figure, rather than choosing a complex, yet correct, interpretation that takes the entire figure into account. We observe that each stair that is one step clockwise from its neighbor is also one step downward, and so we perceive the staircase as eternally descending. In principle, we could instead perceive the figure correctly as depicting four sets of stairs that are discontinuous, and viewed from a unique perspective—however such a percept never occurs.

"The phenomenon of pitch circularity has implications for our understanding of pitch perception, as well as for musical composition and performance."

This paper explores an analogous set of auditory figures that are composed of patterns that appear to ascend or descend endlessly in pitch. Here also, our perceptual system opts for impossible but simple interpretations, based on our perception of local motion in a particular direction–either upward or downward. These sound patterns are not mere curiosities; rather they provide important information concerning general characteristics of pitch perception.

Pitch as a two-dimensional attribute

By analogy with real-world staircases, pitch is often viewed as extending along a one-dimensional continuum of *pitch height*. For sine waves, any significant increase or decrease in frequency is indeed associated with a corresponding increase or decrease in pitch—this is consistent with a one-dimensional representation. However, musicians have long acknowledged that pitch also has a circular dimension, known as *pitch class*—tones that stand in octave relation have a certain perceptual equivalence. The system of notation for the Western musical scale accommodates this circular dimension. Here a note is designated by a letter which refers to its position within the octave, followed by a number which refers to the octave in which the tone occurs. So as we ascend the scale in semitone steps, we repeatedly traverse the pitch class circle in clockwise direction, so that we play C, C#, D, and so on around the circle, until we reach C again, but now the note is an octave higher. Similar schemes are used in Indian musical notation, and in those of other musical cultures.

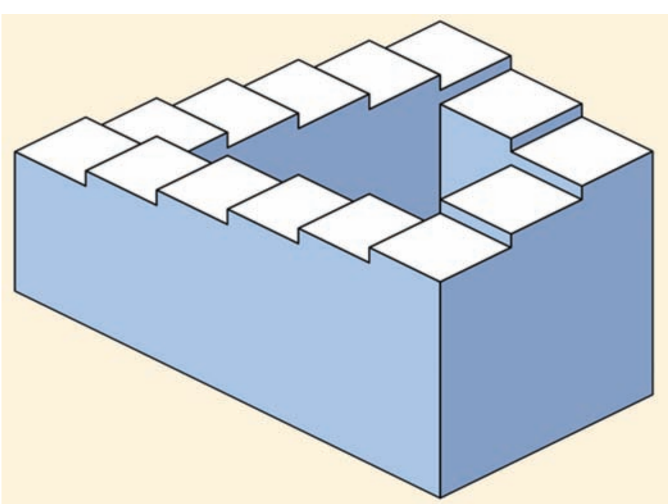


Fig. 1. An impossible staircase, similar to one devised by Penrose and Penrose.[1]

To accommodate both the rectilinear and circular dimensions of pitch, a number of theorists—going back at least to Drobisch in the mid-nineteenth century—have argued that this be represented as a helix having one complete turn per octave, so that pairs of points that are separated by an octave stand in close spatial proximity (Fig. 2). Based on such a representation, Roger Shepard, then at Bell Telephone Laboratories, conjectured that it might be possible to exaggerate the dimension of pitch class and minimize the dimension of height, so that all tones that are related by octaves would be mapped onto a single tone which would have a well-defined pitch class but an indeterminate height. Because the helix would then be collapsed into a circle, judgments of relative pitch for such tones should be completely circular.[2, 3]

Using a software program for music synthesis generated by Max Mathews,[4] Shepard synthesized a bank of complex tones, each of which consisted of 10 partials that were separated by octaves. The amplitudes of the partials were scaled by a fixed, bell-shaped spectral envelope, so that those in the middle of the musical range were highest, while the amplitudes of the others fell off gradually along either side of the log frequency continuum, sinking below the threshold of audibility at the extremes (Fig. 3). Such tones are well defined in terms of pitch class (C, C#, D; and so on) but poorly defined in terms of height, since the other harmonics that would provide the usual cues for height attribution are missing. Using such a bank of tones, one can then vary the dimensions of height and pitch class independently. To vary height alone one can keep the partials constant but rigidly shift the spectral envelope up or down in log frequency; to vary pitch class alone one can rigidly shift the partials in log frequency, while keeping the position of the spectral envelope constant.

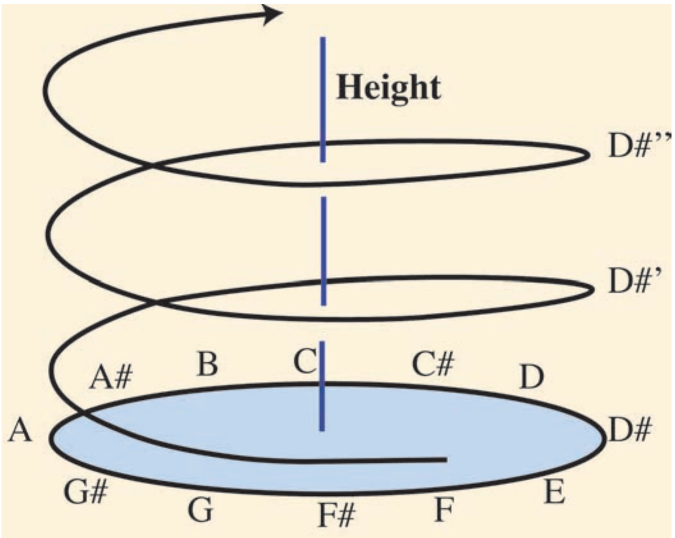


Fig. 2. The helical model of pitch. Musical pitch is depicted as varying along both a linear dimension of height and also a circular dimension of pitch class. The helix completes one full turn per octave, so that tones that stand in octave relation are in close spatial proximity, as shown by D#, D#', and D#."

To demonstrate that such tones have circular properties when the position of the spectral envelope remains fixed, Shepard presented listeners with ordered pairs of such tones, and they judged for each pair whether it formed an ascending or a descending pattern. When the tones within a pair were separated by a small distance along the pitch class circle, judgments of relative height were determined entirely by proximity. As the distance between the tones increased, the tendency to follow by proximity lessened, and when the tones were separated by a half-octave, averaging across pitch classes and across a large group of subjects, ascending and descending judgments occurred equally often.[2]

Shepard then employed such a bank of tones to produce an intriguing demonstration: When the pitch class circle is repeatedly traversed in clockwise steps, one obtains the impression of a scale that ascends endlessly in pitch: C# sounds higher than C; D as higher than C#, D# as higher than D; A# as higher than A; B as higher than A#; C as higher than B; and so on endlessly. One such scale is presented in **Sound Demonstration 1** (See Sidebar). When the circle is traversed in counterclockwise steps, the scale appears to descend endlessly instead. This pitch paradox has been used to accompany numerous videos of bouncing balls, stick men, and other objects traversing the Penrose staircase, with each step accompanied by a step along the Shepard scale.

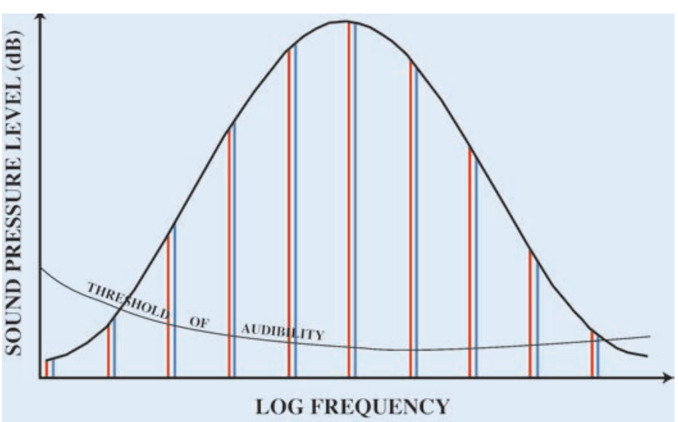


Fig. 3. Spectral representation of Shepard's algorithm for generating pitch circularity. Circularity is obtained by rigidly shifting the partials up or down in log frequency, while the spectral envelope is held fixed. As examples, the red lines represent partials at note C, and the blue lines represent partials at note C#. Adapted from Shepard.[2]

DOWNLOAD THE SOUND DEMO AUDIO CLIPS

Shortly after the print copy of this issue is mailed, it will also be published in the Acoustical Society of America's Digital Library. The Table of Contents may be reached directly by going to your internet browser and typing the following Uniform Resource Locator (URL) in the address block: http://scitation.aip.org/dbt/dbt.jsp?KEY=ATCODK&Volume=6&Issue=3. At some point in the download process you will probably be asked for your ID and Password if you are using a computer that is not networked to an institution with a subscription to the ASA Digital Library. These are the same username and password that you use as an ASA member to access the *Journal of the Acoustical Society of America*. Open the abstract for this article by clicking on Abstract. At the bottom of the abstract will be a link. Click on the link and a zipped folder (DeutschData.zip) will be downloaded to your computer (wherever you usually receive downlinks). Unzip the entire folder (as a whole), save the unzipped folder to your desktop, and open the folder DeutschData. (Note: Before the zip files are extracted, Winzip asks whether you want all files/folders in the current folder unzipped. Check the box that you do. There are 10 demos. Do not remove any file—simply open the file called 00_DeutschOpenMe.pdf. It is an interactive pdf file. By clicking on any of the hyperlink clips in this file, you should hear the audio clip associated with that link. (If your computer says that it cannot find the file when you click on a demo, then the files are still zipped. Unzip the files individually). The best way to enjoy reading the article is to open the magazine. Open the 00_DeutschOpenMe.pdf file on your computer. With mouse in hand, read the article from the magazine and when a demo clip is mentioned, click on the computer link associated with the clip. The author suggests that good computer speakers or earphones will greatly enhance your perception of the subtleties present in the demos. The audio clips were recorded in .WAV format. If you have difficulty in playing it, you might download the PC or MAC version of *VLC Media Player* from www.videolan.org. This is a non-profit organization that has created a very powerful, cross-platform, free and open source player that works with almost all video and audio formats. Questions? Email the Scitation Help Desk at help@scitation.org or call 1-800-874-6383.

Jean-Claude Risset has produced remarkable variants of this illusion, using the same basic principle.[5,6] One set of variants consists of endlessly ascending and descending glissandi. **Sound Demonstration 2** presents an example. In other variants, the dimensions of pitch height and pitch class are decoupled by moving the position of the spectral envelope in the direction opposite that of movement along the pitch class circle.[5, 6] For example, the spectral envelope could be continuously rising, while the tones traverse the pitch class circle in counter-clockwise direction, so that the listener perceives a sequence that both ascends and descends at the same time. Risset has incorporated many of such glides into his compositions, with striking artistic effect. For example, he employed an endlessly descending glissando in the incidental music to Pierre Halet's Little Boy. This play portrays the nightmare of a pilot who took part in the destruction of Hiroshima, and the descending glide symbolizes the falling of the atomic bomb.

Circularities based on spectral proximity

For Shepard tones, there are two ways to interpret the perceptual tendency to form relationships based on pitch proximity. One possibility is that we invoke proximity along the pitch class circle, which is illustrated in Fig. 2. Another possibility is that we connect together the individual partials of the successive tones based on their proximity along the frequency continuum, as illustrated in Fig. 3. That spectral factors alone can produce circularity effects was demonstrated by Jean-Claude Risset[5, 6] when he produced endlessly ascending and descending glissandi consisting of tone complexes whose partials stood in ratios other than an octave. An experimental demonstration of this spectral proximity effect was later produced by Edward Burns, who created banks of tones whose partials were separated by various ratios, ranging from 6 to 16 semitones. He found essentially no difference in circularity judgments depending on whether octave ratios were involved.[7] Other research demonstrating the contribution of spectral proximity to pitch circularity has been carried out by Ryunen Teranishi,[8] and by Yoshitaka Nakajima and his colleagues.[9]

Pitch circularities in musical practice

Although stark pitch circularities were not created until exact control of acoustic parameters became possible in the mid-twentieth century, overall impressions of pitch circularity have been generated by composers from the Renaissance onward.[10] English keyboard music of the sixteenth century, such as composed by Orlando Gibbons, included clever manipulations of tone sequences in multiple octaves so as to create circular effects. In the eighteenth century, J. S. Bach was strikingly effective in devising passages that gave circular impressions, most famously in his organ *Prelude and Fugue in E minor*.

In the early twentieth century, Alban Berg produced an effect that approached that of circularity generated by Shepard tones. In his 1925 opera Wozzeck, Berg employed a continuously rising scale that was orchestrated in such a way that the upper instruments faded out at the top of their range while the lower instruments faded in at the low end. Other twentieth century composers such as Bela Bartok and Gyorgy Ligeti orchestrated sequences that gave rise to circular impressions. In particular, Jean-Claude Risset has made extensive use of circular configurations in his orchestral works; for example in his piece *Phases* he orchestrated circular configurations using harps, celesta, strings, percussion, and brass.

Twentieth century electroacoustic music has also employed circular effects. These occur, for example, in Risset's *Mutations 1*; James Tenny's *For Ann (rising)*, Karlheinz Stockhousen's *Hymnen*, and the Beatle's *A Day in the Life (Sergeant Pepper)*. Recently, Richard King, sound designer for the Batman movie *The Dark Knight*, employed an ever-ascending glide for the sound of Batman's vehicle, the Batpod. Explaining his use of this sound in the Los Angeles Times, King wrote: "*When played on a keyboard, it gives the illusion of greater and greater speed; the pod appears unstoppable.*"[11]

Towards circular banks of musical instrument tones

To achieve pitch circularity, must our choice of musical material be confined to highly artificial tones, or to several instrument tones playing simultaneously? Alternatively, might it be possible to create circular scales from sequences of single tones, with each tone comprising a full harmonic series? If this could be achieved, then the theoretical implications of pitch circularity would be broadened. Furthermore, this would open the door to creating circular banks of tones derived from natural instruments, which would expand the scope of musical materials available to composers and performers.

Arthur Benade stated that a good flautist, while playing a sustained note, can smoothly vary the amplitudes of the odd numbered harmonics relative to the even-numbered ones, so as to produce an interesting effect.[12] Suppose he begins with a note at $F0 = 440$ Hz; the listener hears this as Concert A, well defined in both pitch class and pitch height. If the flautist then alters his manner of blowing so as to progressively reduce the amplitudes of the odd harmonics relative to the even ones, the listener will at some point realize that he is no longer hearing Concert A, but rather the A an octave higher (corresponding to $F0 = 880$ Hz). Yet the transition from the lower to the higher octave can appear quite smooth. Based on this observation, one can surmise further that a tone consisting of a full harmonic series might be made to vary continuously in height between octaves without necessarily traversing the path specified by the helical model, but rather by traversing a straight path upwards or downwards in height—for example between D# and D#' in Fig. 2. Pitch might then be represented as a solid cylinder rather than a helix. **Sound Demonstration 3** presents a harmonic complex tone with $F0 = 440$ Hz, in which the odd harmonics are gradually reduced relative to the even ones, so that the perceived height of the tone moves smoothly up an octave.

In an experiment by Roy Patterson and his colleagues, a set of tones was employed, each of which consisted of the first 28 harmonics, and in which the relative amplitudes of the odd and even harmonics were varied. The subjects' task was to judge the octave in which each tone occurred. Averaging the results across subjects, when the odd harmonics were 27 dB lower than the even ones, listeners judged the tones to be an octave higher; at smaller amplitude discrepancies, averaged judgments of height fell between the higher and lower octaves.[13]

Given these findings, I surmised that one might be able

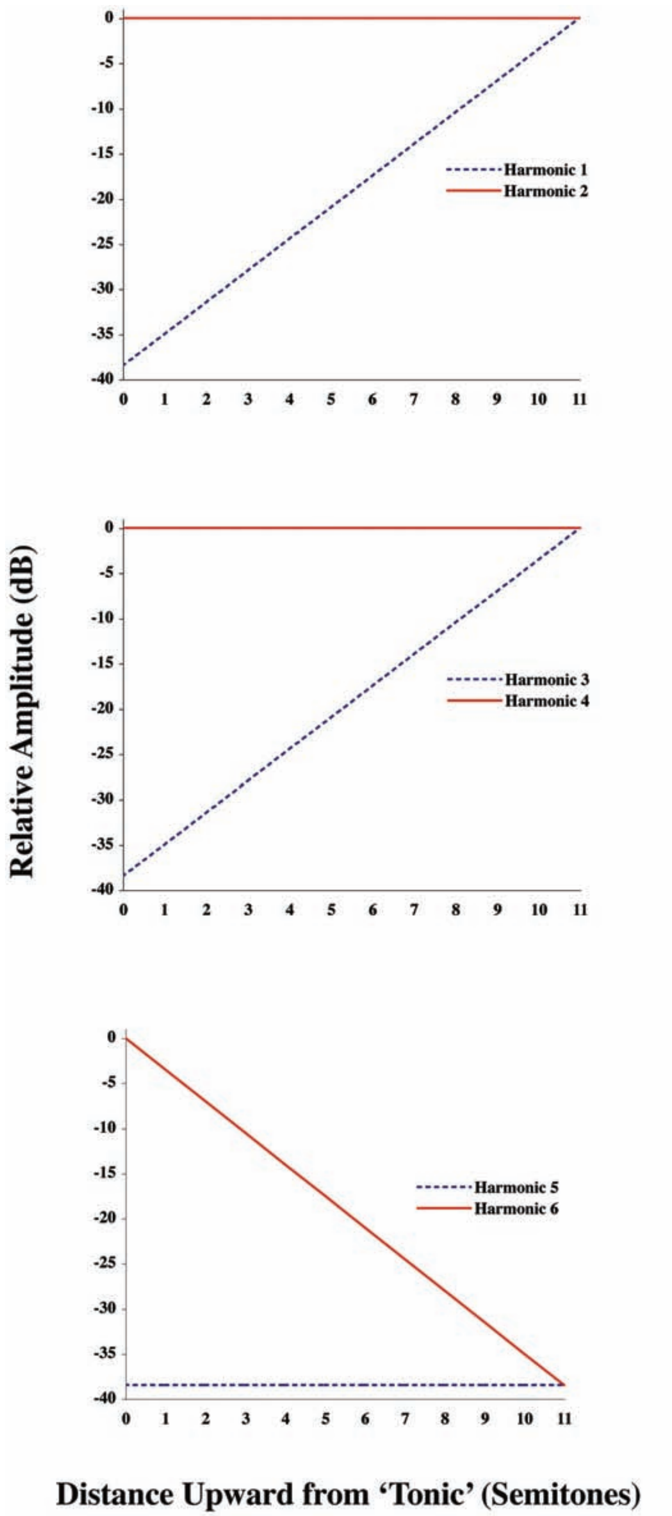


Fig. 4. Algorithm for producing pitch circularity employed by Deutsch.[16] The graphs show the progression of the relative amplitudes of Harmonics 1 and 2, Harmonics 3 and 4, and Harmonics 5 and 6, as F0 moves upward from the 'tonic' of the scale. See text for details. Reprinted from Deutsch, Dooley, and Henthorn.[16]

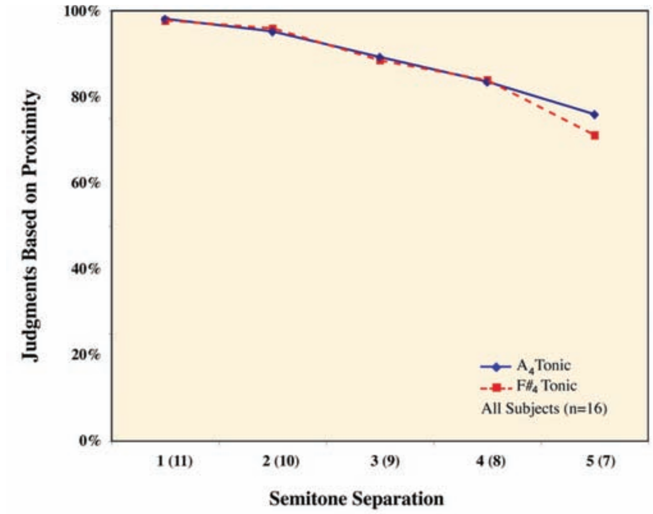


Fig. 5. Subjects were presented with pairs of tones created using the algorithm by Deutsch,[16] and they judged whether each tone pair rose or fell in pitch. The graph plots the percentages of judgments based on pitch class proximity, as a function of distance between the tones within a pair along the pitch class circle. Adapted from Deutsch, Dooley, and Henthorn.[16]

to generate circular banks of tones by systematically varying the relative amplitudes of the odd and even harmonics.[14] We can begin with a bank of twelve tones, each of which consists of the first six components of a harmonic series, with ***F*0s** varying over an octave in semitone steps. For the tone with highest ***F*0** the odd and even harmonics are equal in amplitude. Then for the tone with ***F*0** a semitone lower, the odd harmonics are reduced in amplitude relative to the even ones, so raising the perceived height of the tone. Then for the tone with ***F*0** another semitone lower, the odd harmonics are further reduced in amplitude, so raising the perceived height of the tone to a greater extent. We continue moving down the octave in semitone steps, reducing the amplitudes of the odd-numbered harmonics further with each step, until for the lowest ***F*0** the odd-numbered harmonics no longer contribute to perceived height. The tone with the lowest ***F*0** is therefore heard as displaced up an octave, and so as higher in pitch than the tone with the highest ***F*0**—and pitch circularity is thereby obtained.

After some trial and error, I settled on the parameters shown in Fig. 4. Complex tones consisting of the first six harmonics were employed, and the amplitudes of the odd-numbered harmonics were reduced by 3.5 dB for each semitone step down the scale; therefore for the tone with lowest ***F*0** the odd harmonics were 38.5 dB lower than the even ones. To achieve this pattern for harmonic pairs 1 and 2, and harmonic pairs 3 and 4, the even numbered harmonics were at a consistently high amplitude, while the odd numbered harmonics decreased in amplitude as ***F*0** descended. To obtain the same pattern of relationship for harmonic pairs 5 and 6, harmonic 5 was consistently low in amplitude while harmonic 6 increased in amplitude as the scale descended.

In a formal experiment to determine whether such a bank of tones—hereafter referred to as a scale—would indeed be perceived as circular, my colleagues Trevor Henthorn, Kevin Dooley and I created two such scales;[15] for one scale the lowest ***F*0** was A_4 and for the other the lowest ***F*0** was F#$_4$. (For want of a better word, we refer to the tone with the lowest ***F*0** as the *tonic* of the scale) For each scale, each tone was paired with every other tone, both as the first and the second tone of a pair, and subjects were asked to judge for each pair whether it rose or fell in pitch.

We found that judgments of these tones were overwhelmingly determined by proximity along the pitch class

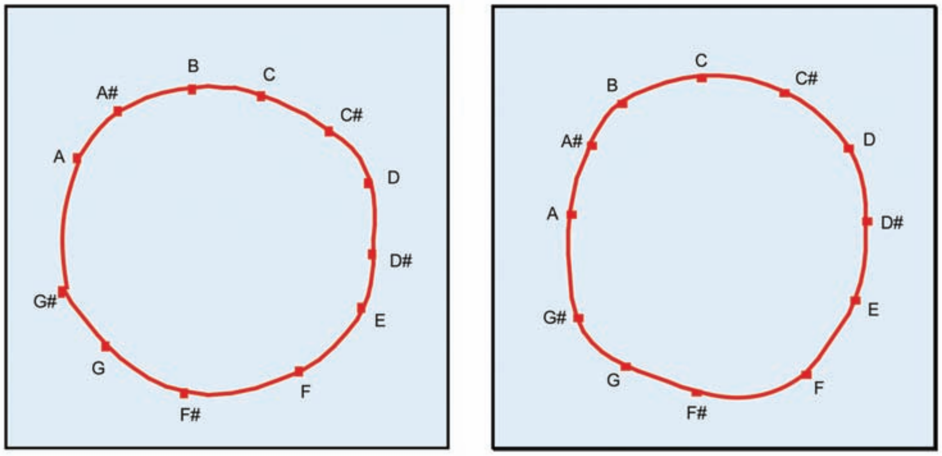


Fig. 6. Multidimensional scaling solutions produced from the relative pitch judgments of tones created using the algorithm of Deutsch,[16] made by an individual subject. The plot on the left shows the solution for tones in the scale based on the A4 tonic, and the plot on the right shows the solution for tones in the scale based on the F#4 tonic. Adapted from Deutsch, Dooley, and Henthorn.[16]

circle.[16] Figure 5 shows the percentages of judgments that were in accordance with proximity, for both scales, and averaged across all subjects. As can be seen, when the tones within a pair were separated by a semitone, proximity determined their judgments almost entirely. As with Shepard's experiment on octave-related complexes, as the tones within a pair were separated by a larger distance along the pitch class circle, the tendency to follow by proximity lessened. And even when the tones were separated by almost a half-octave, the tendency for judgments to follow the more proximal relationship was very high. When we subjected the data to Kruskal's nonmetric multidimensional scaling, we obtained strongly circular solutions, as illustrated in those from an individual subject shown in Fig. 6. We also created sound demonstrations based on this algorithm. These included endlessly ascending and descending scales moving in semitone steps, and endlessly ascending and descending glissandi, and are presented as **Sound Demonstrations 4 - 7**.

The finding that circular scales can be obtained from full harmonic series leads to the intriguing possibility that this algorithm could be used to transform banks of natural instrument tones so that they would also exhibit pitch circularity. William Brent, then a graduate student at the University of California, San Diego music department, has shown that such transformations can indeed be achieved. He used bassoon samples taken from the Musical Instrument Samples Database at the University of Iowa Electronic Music Studios, ranging in semitone steps from D#2 to D3. Using continuous overlapping Fourier analysis, he transformed the sounds into the frequency domain, and there reduced the amplitudes of the odd harmonics by 3.5 dB per semitone step downward. He then performed inverse Fourier transforms to generate the altered waveforms in the time domain. Circular banks of bassoon tones were thereby produced.[17] Endlessly ascending and descending scales employing these tones are presented as **Sound Demonstrations 8 and 9**.

It remains to be determined which types of instrument sound can be transformed so as to acquire this property. However, Brent has also achieved some success with flute, oboe, and violin samples, and has shown that the effect is not destroyed by vibrato. The Digital Signal Processing (DSP) module to produce these transformations was created for the Pd Programming environment,[15, 17] so that composers and performers can now begin to experiment with this algorithm live and in real time, as well as in recording contexts.

Hypothesized neuroanatomical substrates

What do we know about the neuroanatomical substrates underlying the circular component of pitch? An interesting study by J. D. Warren and colleagues sheds light on this issue.[18] These researchers used functional magnetic resonance imaging (fMRI) to explore patterns of brain activation in response to two types of tone sequence. In the first type, the harmonic components of the tones were at equal amplitude, but ***F***0 was varied, so that pitch class and pitch height varied together. In the other type of sequence, pitch class was kept constant but the relative amplitudes of the odd and even harmonics were varied, so that only differences in pitch height were produced. Presentation of the first type of sequence resulted in activation specifically in an area anterior to the primary auditory cortex, while the second type of sequence produced activation primarily in an area posterior to this region. Based on these findings, the authors concluded that the circular component of pitch is represented in the anterior region.

Pitch circularity might, however, have its origins earlier in the auditory pathway. Gerald Langner has provided evidence in the gerbil that the ventral nucleus of the lateral lemniscus is organized in terms of a neuronal pitch helix, so that pitches are arranged in helical fashion from top to bottom with one octave for each turn of the helix.[19] This indicates that the lateral lemniscus might be the source of the circular component, and that it is further represented in the cortex.

A paradox within a paradox

There is an additional twist to the paradox of pitch circularity. We have seen that when listeners are presented with ordered pairs of tones that are ambiguous with respect to height, they invoke proximity along the pitch class circle in making judgments of relative pitch. But we can then ask what happens when a pair of such ambiguous tones is presented which are separated by a half-octave (or tritone) so that the same distance along the circle is traversed in either direction.

For example, what happens when the pattern C-F# is presented? Or the pattern A#-E? Since proximity cannot then be invoked, will such judgments be ambiguous, or will something else occur?

I conjectured that for such patterns, the auditory system would not settle for ambiguity, but would instead make reference to the absolute positions of the tones along the pitch class circle, so that tones in one region of the circle would be heard as higher and tones in the opposite region as lower. This conjecture was confirmed in a series of experiments employing Shepard tones consisting of six octave-related components, with tones within a pair generated under the same spectral envelope.[20] The experimental design controlled for sources of artifact—for example tones were generated under envelopes that were placed in different positions along the spectrum. [21,22, 23,24] Judgments of relative pitch were found to depend in an orderly fashion on the positions of the tones along the pitch class circle.

Another and entirely unexpected finding also emerged from these studies—the orientation of the pitch class circle with respect to height varied strikingly across listeners. For example, some subjects would hear the tone pair D-G# (and C#-G, and D#-A) as ascending, whereas others would hear the same patterns as descending. Then the first set of subjects would hear the tone pair G#-D (and G-C#, and A-D#) as descending while the second set of subjects would hear these patterns as ascending. Such individual differences can be easily demonstrated by presenting the four tritone pairs in **Sound Demonstration 10** to a group of listeners, and asking them to respond with a show of hands whether each tone pair ascended or descended in pitch. This demonstration is particularly striking when played to a group of professional musicians, who are quite certain of their own judgments and yet recognize that others are obtaining entirely different percepts.

In other experiments, R. Richard Moore, Mark Dolson and I studied two-part melodic patterns composed of the same octave-related complexes, and found that judgments here also depended on the positions of the tones along the pitch class circle.[25,26] In general, the tritone paradox and related paradoxes formed of two-part patterns show that while pitch height and pitch class are in principle separate dimensions, one dimension can influence the other.

Summary and conclusions

The phenomenon of pitch circularity has implications for our understanding of pitch perception, as well as for musical composition and performance. It is likely to intrigue acousticians, mathematicians, and musicians for many years to come. The experiments and sound demonstrations described here indicate that the classical definition of pitch as "that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from high to low" [27] should be amended to include the circular dimension also. The experimental decoupling of the linear and circular components of pitch provides a useful tool for the further investigation of the neural underpinnings of these two components, which are presumably processed separately at some stage in the auditory system. For musicians the development of new software that largely decouples pitch class and pitch height, and does so in real time, has opened up intriguing new avenues for composition and performance. **AT**

References and links:

1 L. S. Penrose and R. Penrose, "Impossible objects: A special type of visual illusion," British J. Psychol. **49**, 31-33 (1958). Unknown to the authors, Oscar Reutesvald had also created an impossible staircase in the 1930s.
2 R. N. Shepard, "Circularity in judgments of relative pitch," J. Acoust. Soc. Am. **36**, 2345–2353 (1964).
3 R. N. Shepard, "Structural representations of musical pitch," in *The Psychology of Music*, 1st Edition, edited by D. Deutsch (Academic Press, New York, 1982), pp. 343–390.
4 M. V. Mathews, "The digital computer as a musical instrument," Science **142**, 553–557 (1963).
5 J. C. Risset, "Pitch control and pitch paradoxes demonstrated with computer-synthesized sounds," J. Acoust. Soc. Am. **46**, 88 (1969).
6 J. C. Risset, "Paradoxes de hauteur," ("Paradoxes of height") Proceedings of the 7th International Congress on Acoustics, Budapest, S10, 613-616 (1971).
7 E. Burns, "Circularity in relative pitch judgments for inharmonic complex tones: The Shepard demonstration revisited, again," Perception & Psychophysics **30**, 467–472 (1981).
8 R. Teranishi, "Endlessly ascending/descending chords performable on a piano," Reports of the Acoustical Society of Japan, H, 82–68 (1982).
9 Y. Nakajima, T. Tsumura, D. Matsuura, H. Minami, and R. Teranishi, "Dynamic pitch perception for complex tones derived from major triads," Music Perception **6**, 1–20 (1988).
10 I. Braus, "Retracing one's steps: An overview of pitch circularity and Shepard tones in European music, 1550–1990," Music Perception **12**, 323–351 (1995).
11 R. King, "'The Dark Knight' sound effects," *Los Angeles Times*, February 4, 2009.
12 A. H. Benade, *Fundamentals of Musical Acoustics* (Oxford University Press, New York, 1976).
13 R. D. Patterson, "Spiral detection of periodicity and the spiral form of musical scales," Psychology of Music, **14**, 44–61 (1986).
14 D. Deutsch, "Some new pitch paradoxes and their implications," in *Auditory Processing of Complex Sounds*. Philosphical *Transactions of the Royal Society, Series B*, 1992, 336, 391–397.
15 The tones were created using Miller Puckette's software Pd, which is posted at http://crca.ucsd.edu/~msp/software.html
16 D. Deutsch, K. Dooley, and T. Henthorn, "Pitch circularity from tones comprising full harmonic series," J. Acoust. Soc. Am. **124**, 589–597 (2008).
17 The DSP module created by Brent to generate these bassoon scales is posted at http://williambrent.conflations.com/.
18 J. D. Warren, S. Uppenkamp, R. D. Patterson, and T. D. Griffiths, "Separating pitch chroma and pitch height in the human brain," Proceedings of the Natl. Acad. Sci. of the USA. **100**, 10038–10042 (2003).
19 G. Langner, "Neuronal mechanisms underlying the perception of pitch and harmony," Annals New York Acad. Sci. **1060**, 50–52 (2005).
20 The tones were generated using a software package created by F. Richard Moore and Mark Dolson in the cmusic programming environment (http://www.crca.ucsd.edu/cmusic).
21 D. Deutsch "A musical paradox," Music Perception **3**, 275–280 (1986).
22 D. Deutsch, "The tritone paradox: Effects of spectral variables," Perception & Psychophysics **41**, 563–575 (1987).
23 D. Deutsch, W. L. Kuyper, and Y. Fisher, "The tritone paradox: Its presence and form of distribution in a general population," Music Perception **5**, 79–92 (1987).
24 D. Deutsch, "Processing of pitch combinations," in *The Psychology of Music, 2nd Edition*, edited by D. Deutsch, (Academic Press, San Diego, 1999), pp. 349–412.
25 D. Deutsch, F. R. Moore, and M. Dolson, "The perceived height of octave-related complexes," J. Acoust. Soc. Am. **80**, 1346–1353 (1986).
26 D. Deutsch, "The semitone paradox," Music Perception **6**, 115–132 (1988).
27 American National Standards Institute (ANSI), New York, 1973.

Diana Deutsch is Professor of Psychology at the University of California, San Diego. She obtained her B.A. from Oxford University, and her Ph.D. from the University of California, San Diego. Her work primarily involves perception and memory for sounds, particularly music. Deutsch has been elected Fellow of the *Acoustical Society of America*, the *American Association for the Advancement of Science*, the *Audio Engineering Society*, the *Society of Experimental Psychologists*, the *American Psychological Society*, and the *American Psychological Association*. She was Founding President of the *Society for Music Perception and Cognition*, and Founding Editor of the journal *Music Perception*. She has served as Governor of the *Audio Engineering Society*, as Chair of the Section on Psychology of the *American Association for the Advancement of Science*, as President of Division 10 of the *American Psychological Association*, and as Chair of the *Society of Experimental Psychologists*. She was awarded the *Rudolf Arnheim Award for Outstanding Achievement in Psychology and the Arts* by the *American Psychological Association* in 2004, and the *Gustav Theodor Fechner Award for Outstanding Contributions to Empirical Aesthetics* by the *International Association of Empirical Aesthetics* in 2008.

THE MUSICIAN'S AUDITORY WORLD

Nina Kraus
Northwestern University
Departments of Communication Sciences,
Neurobiology and Physiology, Otolaryngology
Evanston, Illinois 60208

Trent Nicol
Northwestern University
Department of Communication Sciences
Evanston, Illinois 60208

www.brainvolts.northwestern.edu

Introduction

Will listening to Radiohead make you smarter? Probably not. But according to noted Internet data miner Virgil Griffith,[1] the typical Radiohead fan scores about 110 points higher on the Scholastic Aptitude Test (SAT) than the typical Grateful Dead fan (Fig. 1). Of course as we all know, correlation does not equal causation. But, to quote Aniruddh Patel,[2] music is a "transformative technology of the mind," and we know that music does have a very real effect on skills outside the realm of air guitar. The quest to determine the mechanisms for this transference of musical skills has already begun.

In the Kraus lab at Northwestern University, the skills that interest us most are reading and speech-in-noise (SIN) perception. Significantly, musicians excel at these very activities. Our research has led us to measuring deep-brain electroencephalograph (EEG) in response to a variety of complex stimuli, and we have found correlates in this subcortical activity to reading and listening-in-noise skills. A logical step was to look at the interaction between SIN perception and reading and the changes in biology brought about by active engagement with music.

"Brainstem evoked responses to music and speech alike are rich sources in the investigation of music training's role in shaping the nervous system."

Background

Musicians' special skills

As interesting as questions of musical taste and the consequences of favoring one sort of music over another might be, in this report, we will focus on active musical practice. The extent to which musicians are or are not better than their non-musician peers at a variety of tasks that has received considerable attention.

For example, it appears that musicians have particularly good verbal memory[3,4] and auditory-attention skills[5] but not

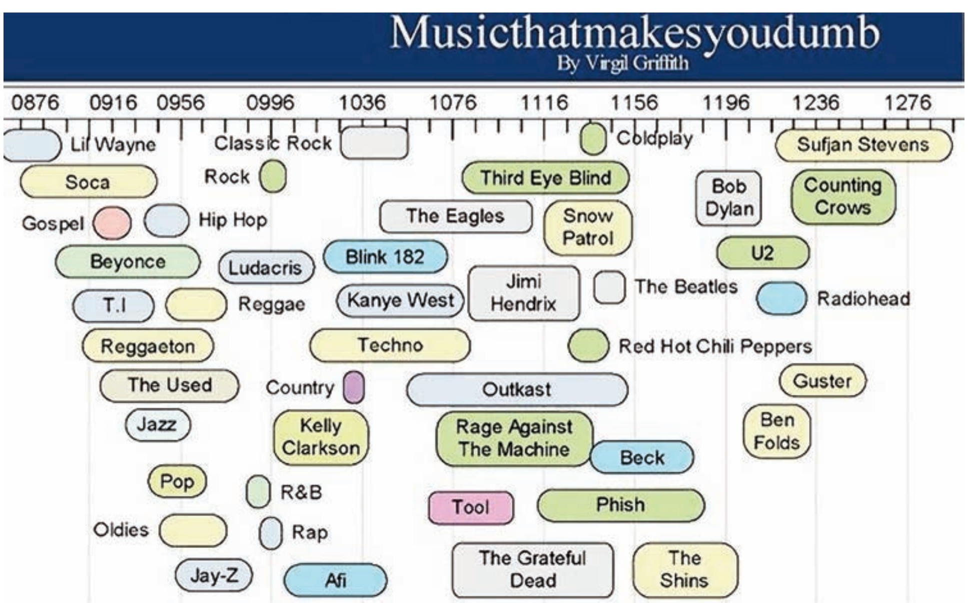


Fig. 1. Average SAT scores for college students who report a given artist or genre as a favorite. See musicthatmakesyoudumb.virgil.gr for additional data and an explanation of derivation. Reprinted with permission of author.

necessarily visual attention. Whether visual memory is superior in musicians is a matter of some debate.[3,6] The extent to which musicians identify emotion in voices or melodies exceeds that of non-musicians,[7] as does the ability to form distinct auditory streams from simultaneously-occurring sounds.[8] Visuospatial skills and certain math skills are also superior in young musicians,[9] as is their performance on executive-function tasks.[10]

Despite these findings, the chicken or egg question arises—does musical training stimulate prowess in these skills or are people who already excel in such arenas more likely to pick up an instrument? Some compelling evidence to support the former scenario comes from correlational studies. If inherent skill X leads to a predisposition toward music, there should be no particular relationship between extent of X prowess and years of musical study. However, such relationships indeed exist. To name a few, the length of musical training in children is predictive of vocabulary knowledge and nonverbal reasoning skills.[11] A variety of IQ measures are associated with duration of music lessons in primary-school children.[12] The other strong bit of evidence that music training leads to brain differences comes from longitudinal studies. After one year of musical training in children, auditory discrimination and fine motor skills increase,[13] and after three years, improvements in vocabulary and non-verbal reasoning skills are seen.[11] Even shorter periods of training result in increases in reading and pitch discrimination compared to children who were randomly selected to receive painting instruction.[14]

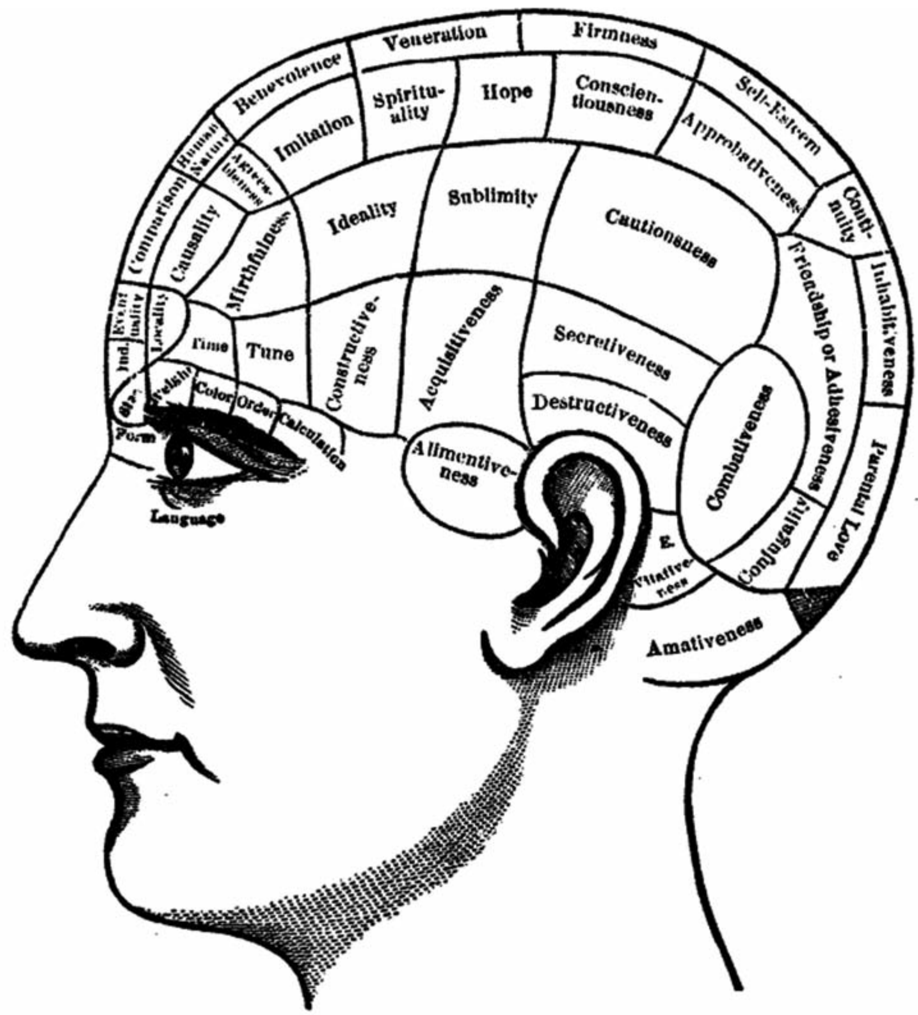


Fig. 2. The music organ, labeled "tune" here, is not far from "time" and "mirthfulness." People with very large tune organs, among other things, "learn tunes by hearing them sung once; sing in spirit and with melting pathos;…sing from the soul to the soul." From Fowler and Fowler, 1889.[144] Electronic resource courtesy of University of Michigan Library.

The musician brain

As we all know, the organ of music is "located immediately above the external angle of the eye and, when it is very developed, results in square foreheads,"—Franz Joseph Gall, quoted in Bentivoglio[15] (Fig. 2). Maybe. But foreheads aside, it stands to reason that, given the many behavioral advantages in musicians, there must be parts of the brain that—either structurally or functionally—differ in musicians. Efforts to localize and quantify these differences date back at least a hundred years,[15] with anecdotal accounts going back even further. The convolutions of Beethoven's brain were said to be "twice as numerous and the fissures twice as deep as in ordinary brains,"—Johann von Seyfried, quoted in Spitzka.[16]

More recently, imaging techniques have revealed structural differences in a variety of musician-brain regions. Just a few examples: gray matter volume of professional musicians is greater than in amateur musicians, who in turn have greater volume than non-musicians, in auditory, visuospatial and motor regions of the brain.[17] Somatosensory cortical areas mapped to the left hand are larger than those mapped to the right hand (and compared to either hand in non-musicians) in string-instrument musicians, tracking with the much larger demands for precise left-hand movement in string players.[18] White matter in the pyramidal tract is more structured in pianists than non-musicians.[19] A recent longitudinal study supports the idea that it is music training itself that induces structural brain enhancement in musicians, rather than existing brain differences encouraging certain individuals to take up music.[20]

Functional differences—measured by neurophysiological and functional imaging techniques—add more evidence of musicianship's role in shaping the brain. Oscillatory gamma-band activity in the brain, related to attention and memory, is enhanced in musicians.[21] A host of cortical evoked neurophysiological responses[22-24] and cortical activation patterns[25] are enhanced in musicians compared to non-musicians. Speeded maturation of cortical potentials is seen in trained children, and seems to accelerate their development by about three years.[26] Additional evidence that music training is causing brain differences, rather than brain differences leading to musical proclivity comes from a study in which very young children in matched musically-trained and untrained cohorts were followed for a year and brain development between groups differed.[27] Research on instrumentalists who play different instruments reveals specialized activations. Gamma-band oscillatory activity in the brain is strongest when induced by the sound of a musician's own instrument.[28] Cortical evoked responses also are preferentially tuned to one's own instrument.[28,29]

Common and separate mechanisms

Turning back to reading and speech-in-noise perception, there are some noteworthy similarities in the skills required for these tasks and for playing a musical instrument. Two such skills, more on the cognitive end of the spectrum, are attention and working memory.

Another crucial need for all three endeavors is accurate processing of incoming auditory signals. The spoken word and music can be thought to consist of three fundamental components: *pitch, harmonics,* and *timing*. These three components of any acoustic signal can be differentiated by their time scales and carry different informational content. In speech, timing and harmonics convey the phonetic content—specific consonants and vowels—of non-tonal languages such as English, and thus are mainly responsible for the verbal message. Pitch conveys intent (e.g., question versus statement) and plays a large role in distinguishing one talker from another. In tonal languages such as Mandarin, pitch also carries linguistic information. In music, one could argue for similar divisions and classifications, but it is all to easy to be trapped into stretching a metaphor. What is information in music? What is intent? Suffice to say, music, even an individual note played by a single instrument, has a rich acoustical structure and is, by any definition, "complex." Thus, brainstem evoked responses to music and speech alike are rich sources in the investigation of music training's role in shaping the nervous system.[a]

Forming phonological representations of the sounds comprising words is a crucial building block of reading. A consonant that has a particular voicing onset (timing) and a spectrum of a particular shape (harmonics) is eventually associated by a young reader with, for example, the letter T. The pitch of this combination of sounds—was it spoken by mom, dad, or the funny-looking purple creature on television?—does not affect its phonetic identity. Timing and harmonic features in speech are especially vulnerable in poor readers and pose particular perceptual challenges[30-32] while pitch perception is generally intact.

Speech-in-noise perception, on the other hand, presents a different set of problems and a corresponding set of skills to accomplish it. Among these are keying in on location cues, stream segregation, and grouping of the acoustic scene.[33-44] Together, these are used to tag and follow the speaker's voice, and rely on pitch[43-48] as well as the timing and harmonic properties of the signal.

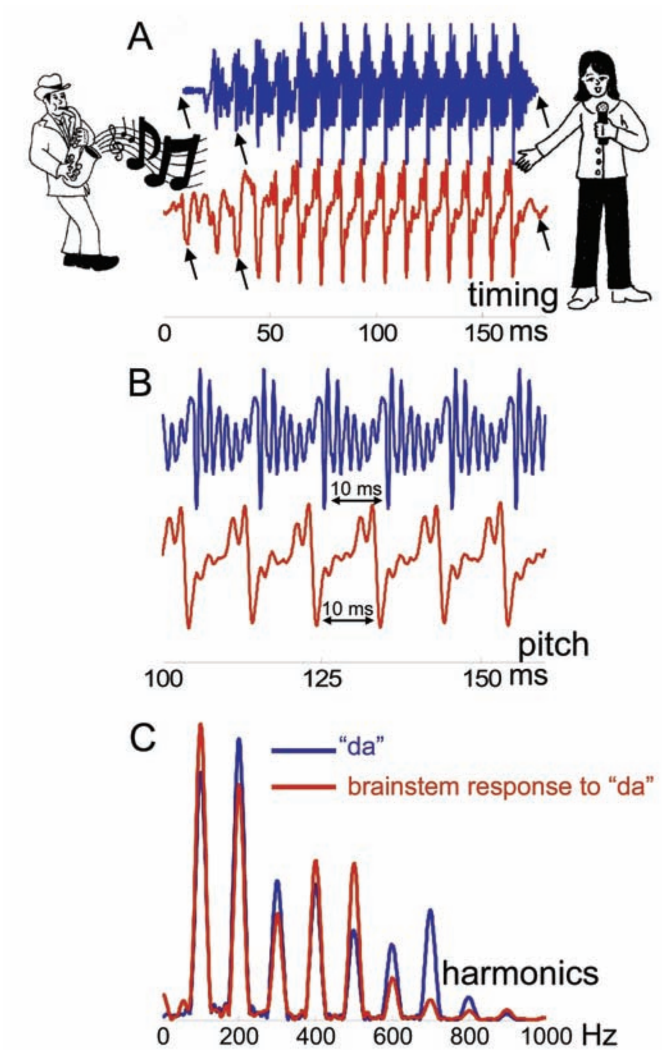


Fig. 3. Timing, pitch and harmonics describe complex acoustic signals: the acoustic waveform of "da" (blue) and its evoked brainstem response (red) on different time scales. A. Prominent timing landmarks of the stimulus, e.g., the onset, offset, and events during time-varying portions (arrows), evoke precisely synchronous and replicable electrical deflections in the auditory brainstem. For illustration purposes, the stimulus waveform in this figure has been delayed in time by 9 ms, to approximate the neural propagation time. This permits better visual coherence between stimulus and response. B. Several repeating periods of 10 ms each are shown. This imparts a pitch percept of 100 Hz, and this periodicity is mirrored in the response. C. Stimulus and response spectra in the frequency domain. Here, the stimulus has been filtered to mimic the response's low-pass characteristic. Spectrum peaks for the stimulus and its evoked auditory brainstem response are exactly aligned, representing their similarity in harmonics. (Artwork by Judy Song.)

Reading, SIN perception and music share a core set of skills—working memory, attention, perception of pitch, timing and harmonics—and each also requires some unique skills. Reading requires the use of phonology and the development of a vocabulary corpus. SIN perception relies on object formation and grouping, stream segregation, and voice tagging. Music involves knowledge of melody, harmony, and rhythm. The skill sets are a mix of low-level sensory processing and high-level cognitive proficiency. A strong *sensory-cognitive* link seems to be a factor in proficiency across domains, and each requires the formation of sound-to-meaning connections. The intersection of common skills, as well as the unique skill sets required for the three, make reading, SIN perception and musical experience an interesting triumvirate to pursue in the investigation of processing of complex sounds in the auditory brainstem. Brainstem activity reflects the acoustical characteristics of signals very well—while plastic to language[49-51] and music[52-56] experience and short-term auditory training,[57,58]—making it well suited to provide objective physiological information about complex-sound encoding in populations with a range of reading, music and SIN perception skills (see Tzounopoulos and Kraus[59] and Skoe and Krause[145] for reviews). Encoding of pitch, timing, and harmonics is selectively diminished in certain clinical populations and selectively enhanced by expertise allowing us to examine specific, separable aspects of signal encoding. We are not observing simple gain effects; that is, overall response disruption or enhancement.

The approach: Music and speech evoked brainstem responses

In the past decade, the Kraus Lab has been a pioneer in the use of speech- and music-evoked auditory brainstem response (ABR) as an innovative objective marker of auditory function in a variety of populations.[49-58;60-113,131] Here, we will present a synopsis of this approach and some advantages over the more widely-studied cortical response and behavioral paradigms.[b]

Neural transcription of the acoustics of sound has been widely studied in the auditory cortex of humans and experimental animals for consonants,[114-116] vowels,[117] and pitch.[118] Structural and functional reorganization of auditory and sensorimotor cortex occur with musical training,[18;27;29;119-121,137] and non-sensory structures also appear to benefit.[122,123] Our focus, and the focus of this review, is on subcortical (auditory brainstem) processing of complex sounds such as speech syllables, musical notes, chords and melodies. Unlike the more abstract representation of sound in the cortex, the brainstem response *resembles and sounds like the evoking sound itself* (Fig. 3). Moreover, responses are reliably stable, interpretable, and meaningful in individuals. The brainstem response paradigm is passive, and its objectivity represents a significant advance over typical measures of complex-sound processing. Most such measures are behavioral in nature, with the person repeating the words that they heard, or making judgments about melodic or rhythmic properties of a musical snippet. Active engagement of processes such as attention, memory, and motor coordination is required to perform the task. Likewise, cortical physiological measures are susceptible to non-sensory factors such as state, motivation, etc. Therefore, our objective brainstem measure is a particularly effective tool at probing unadulterated auditory processing.

While objective, there is another property of the auditory brainstem that is crucial to its value as a window into auditory processing. As mentioned above, it is experience-dependent. On the surface, experience-dependency might seem a counterintuitive property if the principal purpose of the subcortical auditory system is the passive conveyance of acoustic information from receptor to auditory cortex for final and more complex processing. But, not only is there an obligatory system of afferent fibers carrying sensory information from the cochlea to the cortex, but there is also an extensive system of descending efferent fibers that synapse all the way down to the outer hair cells of the cochlea,[124] making plasticity in the brainstem not so implausible.

Now, back to the auditory signal. Many key perceptual ingredients of speech and music are driven by particular properties of the signal and have direct brainstem-response correlates. In response to syllables or musical notes, chords or melodies, the *timing* of the response provides information, on the order of fractions of milliseconds, about the onset and offset of the sounds (i.e., temporal envelope cues), and spectrotemporal patterns in the evoking signal are revealed in response timing and phase.[57,76,125] Analysis of the spectral content of the response provides information about the fundamental frequency, a major contributor to the perceived *pitch* of the signal as well as its *harmonics*, including the temporal fine structure of speech formants and the overtones of a musical note.[82,111,126]

To tie it all together, the components of the brainstem response that are measurably disrupted in poor readers and individuals with poor speech-in-noise perception are the very components that are enhanced in musicians. The connections among the three (music, reading, and speech-in-noise perception), as revealed by the auditory brainstem response, are covered in the next section.

What the brainstem has revealed about the musician's subcortical processing

In this mini-review of recent Kraus-lab investigations, a theme emerges. The subcortical processing augmentations in musicians are selective. Not every aspect of the brainstem response is enhanced, and enhancement does not occur to every stimulus. First, we start with a straight-forward investigation of subcortical processing differences between musicians and non-musicians to musical sounds. Then we look at the degree to which these processing advantages extend to speech, and then to non-speech vocalizations.

Enhancement to music I: Piano chords, Lee et al., 2009.[55] Two-note sampled-piano chords, G-E and F#-E, were used to elicit brainstem responses in a group of adult musicians and an otherwise-matched group of non-musicians. Some interesting aspects of brainstem responses are that they represent the pitch of the evoking signal in their spectra, and that they reveal nonlinear processes by exhibiting frequency components that are not present in the stimuli—namely distortion products or combination tones. These stimuli provided a wealth of response properties for the investigation of musical-signal processing in the rostral brainstem. Interesting findings arose from this investigation. First, of the two primary notes that compose the chord, only representation of the harmonics of the higher note—in both cases E—differed between groups (Fig. 4). Because the musician enhancement was selective, we interpreted the fact that the higher note revealed the group difference as indicative of the relatively greater importance that the upper note typically plays in music. A performing musician is tuned into the melody which is often the highest note of a score. This finding also parallels cortical physiological findings of a larger mismatch response to changes in the upper note of a polyphonic melody.[127] A second finding is that the combination-tone responses, absent in the stimuli, also were enhanced in musicians, providing evidence that these responses probably are of a central origin, and not a result of cochlear non-linearities propagated up to the midbrain.

Enhancement to music II, Linguistic transfer I: Cello and speech. Musacchia et al 2007.[52] Musicians show enhanced processing to speech, not just music. In a design that tested musicians' responses to both music and speech, more evidence of selective enhancement in musicians' subcortical processing emerged. Two stimuli, a bowed cello note and a "da," revealed a musician enhancement. Musicians' phase-locked responses to the fundamental frequencies of both stimuli were enhanced and the extent of enhancement correlated with years of musical practice. This evidence of superior processing in the brainstem in musicians was the first indication of transfer to the speech domain. This study also investigated visual contributions to brainstem auditory processing because of musicians' known ability to better process dual-domain audiovisual stimuli.[128] Here, the two auditory stimuli were presented along with videos of the cello being bowed and a man speaking the syllable. In this presentation mode, similar phase-locking enhancements were seen in musicians, along with faster timing for an onset peak occurring at about 12 ms (Fig. 5). Thus processing of both music and speech and audiovisual interaction in the auditory brainstem appears to benefit from musical experience.

Linguistic transfer II, Tonal languages. Wong et al., 2007.[53] In tonal languages, a single phonetic combination, like "ma," has various meanings depending on the inflection with which it is spoken. In Mandarin, "ma" spoken with a high, level pitch, means "mother." Spoken with a dipping (down then up) pitch, it means "horse." Two other inflections, falling and rising, produce two additional words and these four tones round out the Mandarin repertoire. Other languages have even more tonal markers. It has been demonstrated that pitch-tracking to Mandarin words by the auditory brainstem is more accurate in native Mandarin speakers,[49] likely due to years of tuning engendered by the importance of pitch to their native language. We were interested to see if pitch tracking to Mandarin syllables is improved in individuals whose auditory systems were tuned to pitch for non-linguistic reasons. Non-tonal-language-speaking musicians were chosen for this investigation. Pitch, for musicians, is a critical dimension of their art, and both their auditory systems and their cognitive centers have been extensively honed to it. Brainstem responses to the syllable "mi" with high-level, rising and dipping tones were measured. Accuracy of pitch

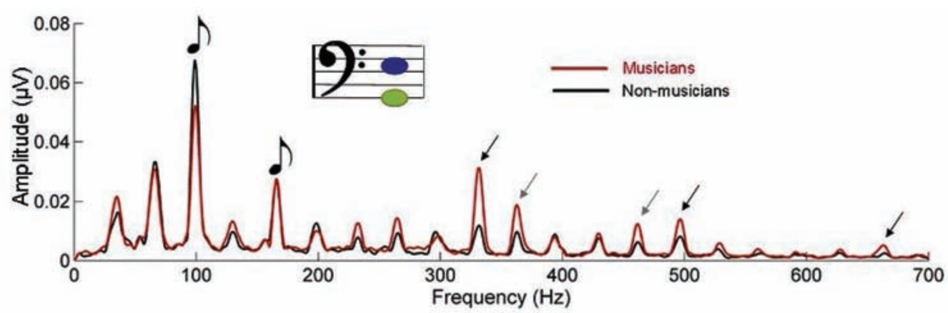


Fig. 4. Musicians have enhanced brainstem representation of the harmonics of the higher note in a chord. No encoding differences were seen at response frequencies corresponding to the two notes comprising the chord (G and E, labeled with musical notes). However, musicians have enhanced encoding at integer harmonics of the higher note (black arrows). Certain combination tones (not present in the chord) also are also more strongly represented in the musician response (gray arrows). Modified from Lee et al., 2009.[55]

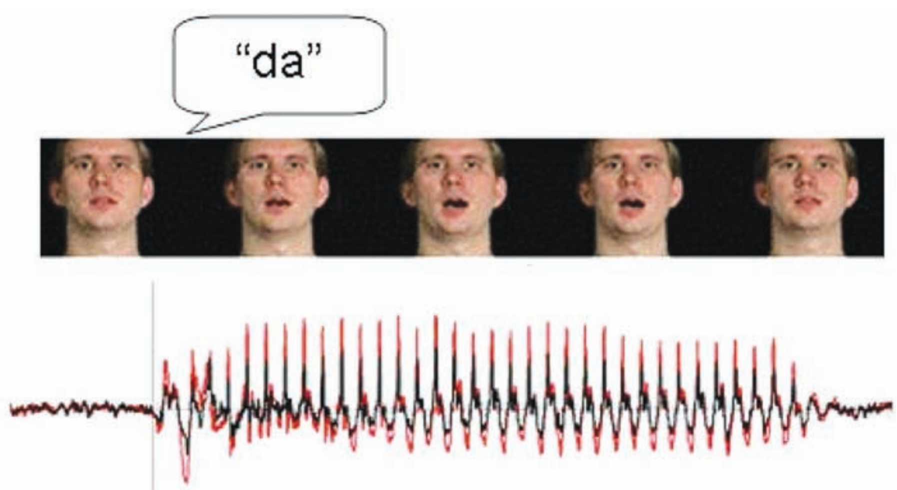


Fig. 5. Whether a "da" is heard by itself or with an accompanying video of its speaker uttering it, the evoked brainstem response is larger in musicians (red). This was the first evidence of linguistic transfer of the musician advantage. Modified from Musacchia et al., 2007.[52]

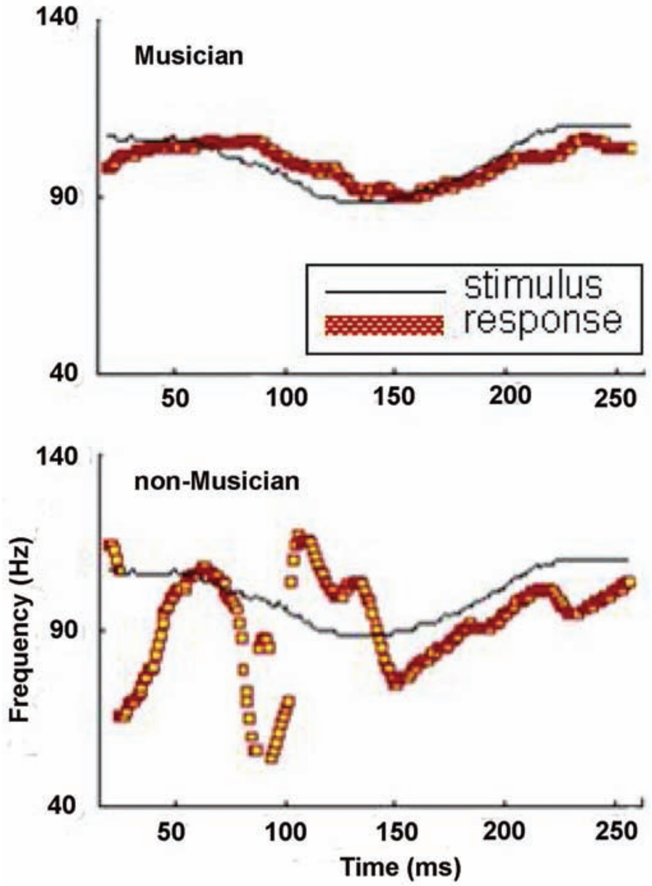


Fig. 6. The voicing contour of this stimulus, "mi," dipped from about 110 Hz, down to 90 Hz and then back up (thin black lines). The precision with which the brainstem response phase locked to the stimulus pitch (thick yellow) was superior in musicians. Modified from Wong et al., 2007.[53]

tracking, measured by how closely in frequency the phase locking in the response matched the changing pitch of the syllables, and strength of phase locking, measured by autocorrelation, both were greater in musicians than in nonmusicians. Notably, the musicians' advantage increased as the complexity of the tone increased (Fig. 6). The most complex, dipping, tone best distinguished the groups, while responses to the level tone differed little between groups. The accuracy of brainstem pitch-tracking of the dipping tone was correlated with the length of musical study, indicating that the differences between groups are likely due to musicianship rather than innate subject differences. This subcortical enhancement in musicians also may provide a mechanism to explain why musicians show a facility for learning foreign languages.[129]

Linguistic transfer III: Speech in noise, Parbery-Clark et al., 2009.[130] One of the biggest communication complaints, affecting school children, hearing impaired individuals, older adults, and everyone in between, is difficulty hearing conversations in noisy backgrounds. While many populations are affected, musicians, in whom stream segregation and object formation are required for parsing melodies from background harmonies, tend to cope with noisy backgrounds especially well. Musicians, in fact, are dramatically better in their ability to hear speech in noise as measured by standardized tests, and this advantage increases with extent of musical experience.[131] Musicians also excel in tasks that test working memory, and this ability relates to speech-in-noise perception. We reasoned that these performance advantages might manifest themselves in a brainstem that better maintains its synchrony in the presence of background noise. Using stimulus-to-response correlations as a metric of brainstem integrity in noise, this was the case. Responses to a speech syllable presented in a quiet background were relatively indistinguishable in normal-hearing adults regardless of their musical backgrounds. However, when the same syllable was masked by multispeaker babble, the musicians' responses maintained an extraordinary degree of robustness, while the nonmusicians' responses deteriorated (Fig. 7). Closer examination of the response spectra revealed that harmonics of the fundamental frequency of the syllable were a source of degradation in the non-musicians. Larger noise-induced delays in discrete peak timing were noted in non-musicians as well. It may be that enhanced processing of these higher-frequency components of sound facilitates the formation of auditory units and thus sets the stage for the stream segregation required for pulling sounds from noise. Thus, the precision in processing complex sounds in the auditory brainstem may be a precursor to successful SIN perception, and brainstem precision in musicians—likely driven by engagement with sound—may undergird their advantage in listening in noise.

Linguistic transfer IV: Regularity detection and reading, Chandrasekaran et al., 2009.[132] The ability to track regularities and to respond appropriately to change are hallmarks of the sensory systems. In the human auditory brainstem, we recently demonstrated that responses to a given sound differ depending on whether that sound is presented in a train by itself or embedded in a series of different sounds.[132] The specific difference, selective enhancements of harmonics two and four in the repetitive condition, has a relationship with behavior. In school-age children, the extent of these enhancements correlates dramatically with reading ability. The sound elements that result in brainstem deficiencies—poor readers in this study and others[88,89,113,125,132]—are the same aspects of auditory processing that are enhanced in musicians.[133,134] We speculate that some common mechanisms are at work. One mechanism might be proficiency at noise exclusion—the ability to extract relevant signals from a jumble of sounds.[135] Cognitive skills such as auditory memory and attention, enhanced in musicians, invoke corticofugal mechanisms that tune brainstem processing. The poorer engagement of cognitive skills in poor readers fails to solidify the corticofugal tuning of brainstem processing of complex sounds.

Vocal emotion, Strait et al 2009.[54] A baby's cry is a mix of harmonic and stochastic sounds strung together into an emotion-evoking signal. The acoustical variety packed into this short quarter-second sample makes this one of our most complex stimuli, and the pattern of response differences seen between musicians and non-musicians again speaks to the selective patterns of enhancement—and in this case also response suppression—engendered by musicianship. Zeroing in on the responses to a harmonic, relatively simple (112–142

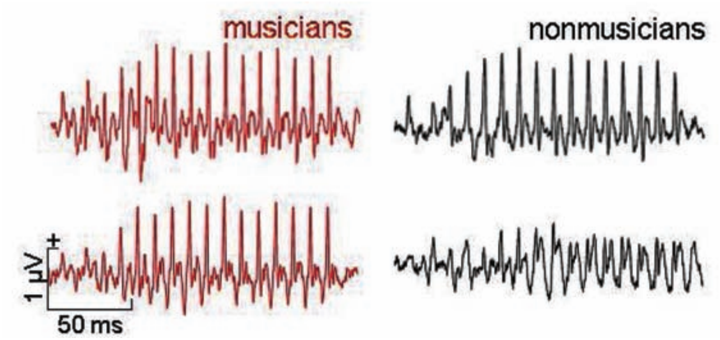


Fig. 7. Degradation in brainstem responses is common when the stimulus is embedded in background noise. While musicians' and non-musicians' responses are similar in quiet (top), the degradation of response morphology in noise (bottom) is minimized in musicians (red). Modified from Parbery-Clark et al., 2009.[130]

ms) segment and a complex non-harmonic (145–212 ms) segment, reveals an interesting pattern. Musicians' responses to the earlier segment are smaller than nonmusicians', while their responses to the later, complex, segment are larger (Fig. 8). This combination of processing strategies—both response efficiency and enhancement—to different types of acoustic stimulation has certain parallels to cortical studies in which musicians show an economy of response to harmonically simple sounds.[136] In contrast, the musician's enhancement to the more complex portion of the baby cry is in line with some of the other processing enhancements we have seen in musicians' auditory brainstems. The results of this investigation demonstrate that subcortical processing differences in musicians extend toward non-musical and non-speech vocal sounds.

Summary and conclusions

As we learn more about the auditory brainstem response to speech and musical sounds, one of the more interesting findings is that the same neural processes that are diminished in poor readers and individuals with difficulty hearing in noise are the same processes that are enhanced in musicians. Neither the deficits nor the enhancements are pan-response. In every case, with peripheral hearing as a strict control, only subtle response characteristics are affected while gross morphology is maintained. This speaks to the value of the brainstem response in the investigation of possible neural origins for reading and SIN perception problems and musical-experience-mediated processing advantages. Not only is the response powerful because of its suitability as an individual-subject probe, but it is many-faceted. That is, its components—each tied inextricably to components of the auditory landscape—are separable; it is not an undifferentiated phenomenon with little relationship to the evoking sound.[82] This gives the researcher a technique to look for selective enhancements or impairments that is unavailable in the more abstract realms of cortical physiology and imaging. The brainstem provides an exciting window into the *sensory-cognitive* reorganization that underpins the changes brought about by engagement with music. With it comes the promise of disambiguating the mechanisms through which these changes occur.

The behavioral, cognitive, cortical, and subcortical advantages bestowed by musical training, serve to promote musical training as a logical strategy for improving basic sound transcription via the reinforcement of reciprocal subcortical-cortical processing interactions brought about, at least in part, by the strengthening of auditory memory and attention. This improved sound transcription, in turn, is a building block of phonological processing, reading, and the extraction of speech from background noise. Further work also can address the extent to which musical practice may serve as protection and remediation against hearing-loss or age-induced communication difficulties and a means to engender the formation of sound-to-meaning relationships that are so critical to human communication.[137] The brainstem response can serve as a potent efficacy measure of music-based education due to its fidelity to the stimulus, its individual-subject reliability, its experience-dependent malleability and its selective nature. Supported by National Science Foundation grants SBE-0842376 and BCS-092275. **AT**

End notes

[a] We are using the terms pitch, timing and harmonics as shorthand throughout this report. We recognize that these constructs have other strict meanings, and that such a tidy differentiation among these three constructs in speech and music is an oversimplification. For our purposes, we refer to pitch as the fundamental frequency (f_0) of a note or an utterance. In speech, f_0 is a

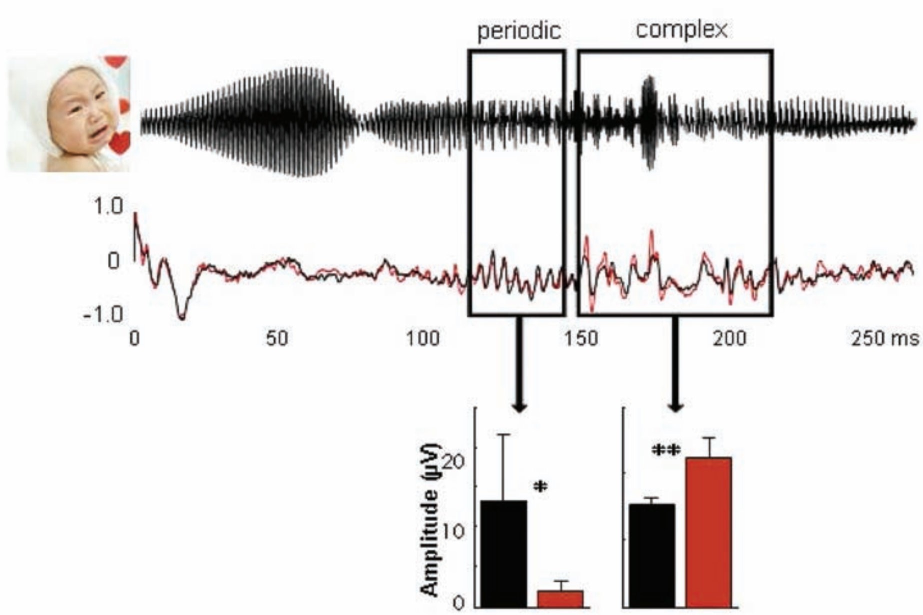


Fig. 8. Musicianship extends to brainstem processing advantages to non-linguistic vocal sounds. The selective nature of music training's impact on processing is revealed within the response to a single baby's cry (top). A complex region of the musician's response (red) is enhanced; a periodic part is reduced. From Strait et al., 2009.[54]

source characteristic and is directly related to the rate of vibration of the vocal folds; in music it is dictated by such things as string length. We recognize that the percept of pitch is not solely conveyed by the fundamental frequency, but pitch is our shorthand for the repeating period of the signal. We define harmonics as the overtones of the fundamental. We recognize that harmonics arise from the same source as the f_0 and also contribute to the percept of pitch. But in music, their relative amplitudes contribute to the identity of the instrument, and in speech, the identity of the particular vowel or consonant that is being spoken. These properties, not their shared origin with the fundamental, put harmonics into a different camp from pitch in our model. Timing refers to the major acoustic landmarks in the temporal envelope of the signal, in speech, arising from the alternating opening and closing of the articulators and from the interplay between laryngeal and supralaryngeal gestures, and in music the rhythmic structure of the phrase. In speech, timing also includes spectrotemporal features of speech such as the changing of formants over time. The three components of our model, pitch, timing and harmonics, as defined here, have direct and separable parallels in the speech- and music-evoked brainstem responses.

b How do we know that what we are recording does not arise from structures more central to the auditory midbrain? We acknowledge that our non-invasive (scalp electrode) technique prohibits certainty of source. We believe that the low-pass characteristic of the auditory system minimizes the possibility that the highly-filtered activity we measure is cortical afferent activity.[110] Moreover, the complex auditory brainstem response (cABR), especially its frequency-following response (FFR) component has been widely studied, and several converging lines of evidence point to a subcortical source. The FFR appears in response to tone pips that are shorter than the time required for cortical propagation.[138] The time delay of the individual FFR cycles, with respect to the evoking stimulus, is around six milliseconds, which is too early for cortical involvement.[139] Animal work[140] added two lines of evidence of a subcortical origin for FFRs: first, based on similarity of latencies of FFRs recorded from cat scalp and brainstem inferior colliculus, and second, from the abolition of surface-recorded responses with cryogenic cooling of inferior colliculus. Additionally, Galbraith[141;142] demonstrated that recordings from the scalp reflect a response of central brainstem origin. However, due to the length of our cABR stimuli—100 milliseconds and up, cortical influence can not be completely ruled out. More probable, is that the responses are a mix of afferent brainstem activity and cortically modulated efferent effects on brainstem function. It also bears mentioning that responses from putative deep-brain sources are less topographically variable than responses from more superficial cortical areas. Much insight on voltage sources is gained by a full topographical array of electrodes in the investigation of cortical responses. However, due to their long travel in propagation to the scalp, speech-ABRs lose site-specificity; hence, little is to be gained by studying their topographic distribution. A single vertex electrode is sufficient.[143]

References

1 V. Griffith, “Music that makes you dumb,” http://musicthatmakesyoudumb.virgil.gr.

2 A. D. Patel. “Music as a transformative technology of the mind,” in Proceedings from John Templeton Foundation Symposium: Music: Its evolution, cognitive basis, and spiritual dimensions, 2008.

3 A. S. Chan, Y. C. Ho, and M. C. Cheung, “Music training improves verbal memory,” Nature **396**, 128–128 (1998).

4 S. Brandler and T. H. Rammsayer, “Differences in mental abilities between musicians and non-musicians,” Psychology of Music **31**, 123–138 (2003).

5 D. Strait, N. Kraus, A. Parbery-Clark, and R. Ashley, “Musical experience shapes top-down auditory mechanisms: Evidence from masking and auditory attention performance,” Hearing Res. **261**, 22–29 (2010).

6 L. S. Jakobson, S. T. Lewycky, A. R. Kilgour, and B. M. Stoesz, “Memory for verbal and visual material in highly trained musicians,” Music Perception **26**, 41-55 (2008).

7 W. F. Thompson, E. G. Schellenberg, and G. Husain, “Decoding speech prosody: Do music lessons help?,” Emotion **4**, 46–64 (2004).

8 B. R. Zendel and C. Alain, “Concurrent sound segregation is enhanced in musicians,” J. Cognitive Neurosci. **21**, 1488–1498 (2009).

9 A. B. Graziano, M. Peterson, and G. L. Shaw, “Enhanced learning of proportional math through music training and spatial-temporal training,” Neurological Res. 21, 139–152 (1999).

10 E. Bialystok and A. M. Depape, “Musical expertise, bilingualism, and executive functioning,” J. Exp. Psychology-Human Perception and Performance **35**, 565–574 (2009).

11 M. Forgeard, E. Winner, A. Norton, and G. Schlaug, “Practicing a musical instrument in childhood is associated with enhanced verbal ability and nonverbal reasoning,” PLoS ONE **3**, e3566 (2008).

12 E. G. Schellenberg, “Long-term positive associations between music lessons and IQ,” J. Educational Psychology **98**, 457–468 (2006).

13 G. Schlaug, A. Norton, K. Overy, and E. Winner, “Effects of music training on the child’s brain and cognitive development,” Annals New York Acad. Sci. **1060**, 219–230 (2005).

14 S. Moreno, C. Marques, A. Santos, M. Santos, S. L. Castro, and M. Besson, “Musical training influences linguistic abilities in 8-year-old children: more evidence for brain plasticity,” Cerebral Cortex **19**, 712–723 (2008).

15 M. Bentivoglio, “Musical skills and neural functions: The legacy of the brains of musicians,” Annals New York Acad. Sci. **999**, 234-243 (2003).

16 E. A. Spitzka, “A study of the brains of six eminent scientists and scholars belonging to the American Anthropometric Society, together with a description of the skull of Professor E. D. Cope,” Trans. Am. Philosophical Soc. **21**, 175–308 (1907).

17 C. Gaser and G. Schlaug, “Brain structures differ between musicians and non-musicians,” J. Neurosci. **23**, 9240–9245 (2003).

18 T. Elbert, C. Pantev, C. Wienbruch, B. Rockstroh, and E. Taub, “Increased cortical representation of the fingers of the left hand in string players,” Science **270**, 305–307 (1995).

19 S. L. Bengtsson, Z. Nagy, S. Skare, L. Forsman, H. Forssberg, and F. Ullen, “Extensive piano practicing has regionally specific effects on white matter development,” Nature Neurosci. **8**, 1148–1150 (2005).

20 K. L. Hyde, J. Lerch, A. Norton, M. Forgeard, E. Winner, A. C. Evans, and G. Schlaug, “Musical training shapes structural brain development,” J. Neurosci. **29**, 3019–3025 (2009).

21 L. J. Trainor, A. J. Shahin, and L. E. Roberts, “Understanding the benefits of musical training effects on oscillatory brain activity,” Neurosci. and Music III: Disorders and Plasticity **1169**, 133–142 (2009).

22 C. Pantev, R. Oostenveld, A. Engelien, B. Ross, L. E. Roberts, and M. Hoke, "Increased auditory cortical representation in musicians," Nature **392**, 811–814 (1998).

23 A. Shahin, D. J. Bosnyak, L. J. Trainor, and L. E. Roberts, "Enhancement of neuroplastic P2 and N1c auditory evoked potentials in musicians," J. Neurosci. **23**, 5545–5552 (2003).

24 T. Fujioka, L. J. Trainor, B. Ross, R. Kakigi, and C. Pantev, "Musical training enhances automatic encoding of melodic contour and interval structure," J. Cognitive Neurosci. **16**, 1010–1021 (2004).

25 P. Schneider, M. Scherg, H. G. Dosch, H. J. Specht, A. Gutschalk, and A. Rupp, "Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians," Nature Neurosci. **5**, 688–694 (2002).

26 A. Shahin, L. E. Roberts, and L. J. Trainor, "Enhancement of auditory cortical development by musical experience in children," Neuroreport **15**, 1917–1921 (2004).

27 T. Fujioka, B. Ross, R. Kakigi, C. Pantev, and L. J. Trainor, "One year of musical training affects development of auditory cortical-evoked fields in young children," Brain **129**, 2593–2608 (2006).

28 A. J. Shahin, L. E. Roberts, W. Chau, L. J. Trainor, and L. M. Miller, "Music training leads to the development of timbre-specific gamma band activity," Neuroimage **41**, 113–122 (2008).

29 C. Pantev, L. E. Roberts, M. Schulz, A. Engelien, and B. Ross, "Timbre-specific enhancement of auditory cortical representations in musicians," Neuroreport **12**, 169–174 (2001).

30 B. de Gelder and J. Vroomen, "Impaired speech perception in poor readers: Evidence from hearing and speech reading," Brain and Language **64**, 269–281 (1998).

31 P. Tallal and R. E. Stark, "Speech acoustic-cue discrimination abilities of normally developing and language-impaired children," J. Acoust. Soc. Am. **69**, 568–574 (1981).

32 P. Tallal, "Auditory temporal perception, phonics, and reading disabilities in children," Brain and Language **9**, 182–198 (1980).

33 A. W. Bronkhorst, "The cocktail party phenomenon: A review of research on speech intelligibility in multiple-talker conditions," Acustica **86**, 117–128 (2000).

34 E. C. Cherry, "Some experiments on the recognition of speech, with one and with two ears," J. Acoust. Soc. Am. **25**, 975–979 (1953).

35 M. Ericson and R. McKinley, "The intelligibility of multiple talkers spatially separated in noise," in *Binaural and Spatial Hearing in Real and Virtual Environments*, edited by R. H. Gilkey and T. R. Anderson (Erlbaum, Hillsdale, NJ, 1997) pp. 701-724.

36 A. S. Bregman, *Auditory Scene Analysis: The Perceptual Organization of Sound* (MIT Press, Cambridge, MA, 1990).

37 B. G. Shinn-Cunningham and V. Best, "Selective attention in normal and impaired hearing," Trends in Amplification **12**, 283–299 (2008).

38 B. G. Shinn-Cunningham, "Why hearing impairment may degrade selective attention," *International Symposium on Auditory and Audiological Research*, Helsingor, Denmark (2007).

39 M. A. Bee and G. M. Klump, "Primitive auditory stream segregation: A neurophysiological study in the songbird forebrain," J. Neurophysiology **92**, 1088–1104 (2004).

40 C. Micheyl, R. P. Carlyon, A. Gutschalk, J. R. Melcher, A. J. Oxenham, J. P. Rauschecker, B. Tian, and E. C. Wilson, "The role of auditory cortex in the formation of auditory streams," Hearing Res. **229**, 116–131 (2007).

41 C. Micheyl, B. Tian, R. P. Carlyon, and J. P. Rauschecker, "Perceptual organization of tone sequences in the auditory cortex of awake Macaques," Neuron **48**, 139–148 (2005).

42 J. S. Snyder and C. Alain, "Toward a neurophysiological theory of auditory stream segregation," Psychological Bulletin **133**, 780–799 (2007).

43 C. J. Darwin and R. W. Hukin, "Effectiveness of spatial cues, prosody, and talker characteristics in selective attention," J. Acoust. Soc. Am. **107**, 970–977 (2000).

44 M. Sayles and I. M. Winter, "Reverberation challenges the temporal representation of the pitch of complex sounds," Neuron **58**, 789–801 (2008).

45 J. P. L. Brokx and S. G. Nooteboom, "Intonation and the perceptual separation of simultaneous voices," J. Phonetics **10**, 23–36 (1982).

46 G. Parikh and P. C. Loizou, "The influence of noise on vowel and consonant cues," J. Acoust. Soc. Am. **118**, 3874–3888 (2005).

47 B. C. J. Moore, B. R. Glasberg, and R. W. Peters, "Relative dominance of individual partials in determining the pitch of complex tones," J. Acoust. Soc. Am. **77**, 1853–1860 (1985).

48 J. Bird and C. J. Darwin, "Effects of a difference in fundamental frequency in separating two sentences," in *Psychophysical and Physiological Advances in Hearing*, edited by A. R. Palmer, A. Rees, A. Q. Summerfield, and R. Meddis (Whurr, London, 1998) pp. 263-269.

49 A. Krishnan, Y. S. Xu, J. Gandour, and P. Cariani, "Encoding of pitch in the human brainstem is sensitive to language experience," Cognitive Brain Res. **25**, 161–168 (2005).

50 J. Swaminathan, A. Krishnan and J. T. Gandour, "Pitch encoding in speech and nonspeech contexts in the human auditory brain-

stem," Neuroreport **19**, 1163–1167 (2008).
51 A. Krishnan, J. Swaminathan, and J. T. Gandour, "Experience-dependent enhancement of linguistic pitch representation in the brainstem is not specific to a speech context," J. Cognitive Neurosci. **21**, 1092–1105 (2009).
52 G. Musacchia, M. Sams, E. Skoe, and N. Kraus, "Musicians have enhanced subcortical auditory and audiovisual processing of speech and music," Proceedings Natl. Acad. of Sci. of USA **104**, 15894–15898 (2007).
53 P. C. M. Wong, E. Skoe, N. M. Russo, T. Dees, and N. Kraus, "Musical experience shapes human brainstem encoding of linguistic pitch patterns," Nature Neurosci. **10**, 420–422 (2007).
54 D. Strait, E. Skoe, N. Kraus, and R. Ashley, "Musical experience and neural efficiency: Effects of training on subcortical processing of vocal expressions of emotion," European J. Neurosci. **29**, 661–668 (2009).
55 K. M. Lee, E. Skoe, N. Kraus, and R. Ashley, "Selective subcortical enhancement of musical intervals in musicians," J. Neurosci. **29**, 5832–5840 (2009).
56 N. Kraus, E. Skoe, A. Parbery-Clark, and R. Ashley, "Experience-induced malleability in neural encoding of pitch, timbre and timing: Implications for language and music," Annals New York Acad. Sci. Neurosci. and Music III **1169**, 543–557 (2009).
57 N. Russo, T. Nicol, G. Musacchia, and N. Kraus, "Brainstem responses to speech syllables," Clinical Neurophysiology **115**, 2021–2030 (2004).
58 J. Song, K. Banai, and N. Kraus, "Brainstem timing deficits in children with learning impairment may result from corticofugal origins," Audiology & Neurotology **13**, 335–344 (2008).
59 T. Tzounopoulos and N. Kraus, "Learning to encode timing: Mechanisms of plasticity in the auditory brainstem," Neuron **62**, 463–469 (2009).
60 D. Abrams, T. Nicol, S. Zecker, and N. Kraus, "Right-hemisphere auditory cortex is dominant for coding syllable patterns in speech," J. Neurosci. **28**, 3958–3965 (2008).
61 N. Kraus and T. Nicol, "Aggregate neural responses to speech sounds in the central auditory system," Speech Communication **41**, 35–47 (2003).
62 N. Kraus, T. McGee, T. Carrell, A. Sharma, and T. Nicol, "Mismatch negativity to speech stimuli in school-age children," Electroencephalography and Clinical Neurophysiology – Supplement **44**, 211–217 (1995).
63 J. Allen, N. Kraus, and A. R. Bradlow, "Neural representation of consciously imperceptible speech-sound differences," Perception & Psychophysics **62**, 1383–1393 (2000).
64 N. Kraus, D. B. Koch, T. J. McGee, T. G. Nicol, and J. Cunningham, "Speech-sound discrimination in school-age children: Psychophysical and neurophysiologic measures," J. Speech, Lang. and Hearing Res . **42**, 1042–1060 (1999).
65 A. R. Bradlow, N. Kraus, T. G. Nicol, T. J. McGee, J. Cunningham, S. G. Zecker, and T. D. Carrell, "Effects of lengthened formant transition duration on discrimination and neural representation of synthetic CV syllables by normal and learning-disabled children," J. Acoust. Soc. Am. **106**, 2086–2096 (1999).
66 N. Kraus, T. McGee, T. D. Carrell, and A. Sharma, "Neurophysiologic bases of speech discrimination," Ear and Hearing **16**, 19–37 (1995).
67 A. Sharma, N. Kraus, T. McGee, T. Carrell, and T. Nicol, "Acoustic versus phonetic representation of speech as reflected by the mismatch negativity event-related potential," Electroencephalography and Clinical Neurophysiology **88**, 64–71 (1993).
68 N. Kraus, T. McGee, T. Carrell, A. Sharma, A. Micco, and T. Nicol, "Speech-evoked cortical potentials in children," J. Am. Acad. Audiol. **4**, 238–248 (1993).
69 N. Kraus, T. McGee, A. Micco, A. Sharma, T. Carrell, and T. Nicol, "Mismatch negativity in school-age children to speech stimuli that are just perceptibly different," Electroencephalography and Clinical Neurophysiology **88**, 123–130 (1993).
70 N. Kraus and M. Cheour, "Speech sound representation in the brain," Audiology & Neurotology **5**, 140-150 (2000).
71 J. H. Song, K. Banai, N. Russo, and N. Kraus, "On the relationship between speech and nonspeech evoked auditory brainstem response," Audiology & Neurotology **11**, 233–241 (2006).
72 A. Sharma, N. Kraus, T. J. McGee, and T. G. Nicol, "Developmental changes in P1 and N1 central auditory responses elicited by consonant-vowel syllables," Electroencephalography and Clinical Neurophysiology **104**, 540–545 (1997).
73 J. Q. Wang, T. Nicol, E. Skoe, M. Sams, and N. Kraus, "Emotion modulates early auditory response to speech," J. Cognitive Neurosci. **21**, 2121–2128 (2009).
74 J. Hornickel, E. Skoe, and N. Kraus, "Subcortical laterality of speech processing," Audiology & Neurotology **14**, 198–207 (2009).
75 D. Abrams and N. Kraus, "Auditory pathway representation of speech sounds in humans," in *Handbook of Clinical Audiology*, edited by J. Katz, L. Hood, R. Burkard, and L. Medwetsky (Lippincott, Williams & Wilkins, Philadelphia, 2009) pp. 611-626.
76 K. L. Johnson, T. Nicol, S. G. Zecker, A. R. Bradlow, E. Skoe, and N. Kraus, "Brainstem encoding of voiced consonant-vowel stop syllables," Clinical Neurophysiology **119**, 2623–2635 (2008).
77 K. L. Johnson, T. Nicol, S. G. Zecker, and N. Kraus, "Developmental plasticity in the human auditory brainstem," J. Neurosci. **28**, 4000–4007 (2008).
78 K. L. Johnson, T. Nicol, S. Zecker, and N. Kraus, "Auditory brainstem correlates of perceptual timing deficits," J. Cognitive Neurosci. **19**, 376–385 (2007).
79 J. Song, E. Skoe, P. C. M. Wong, and N. Kraus, "Plasticity in the adult human auditory brainstem following short-term linguistic training," J. Cognitive Neurosci. **20**, 1892–1902 (2008).
80 D. Abrams, T. Nicol, S. Zecker, and N. Kraus, "Auditory brainstem timing predicts cerebral asymmetry for speech," J. Neurosci. **26**, 11131–11137 (2006).
81 G. Musacchia, M. Sams, T. Nicol, and N. Kraus, "Seeing speech affects acoustic information processing in the human brainstem," Experimental Brain Res. **168**, 1–10 (2006).
82 N. Kraus and T. G. Nicol, "Brainstem origins for cortical 'what' and 'where' pathways in the auditory system," Trends in Neurosci. **28**, 176–181 (2005).
83 J. Song, E. Skoe, K. Banai, and N. Kraus, "Perception of speech in noise: Neural Correlates, J. Cognitive Neurosci. (2010, in press).
84 C. King, C. M. Warrier, E. Hayes, and N. Kraus, "Deficits in auditory brainstem encoding of speech sounds in children with learning problems," Neurosci. Letters **319**, 111–115 (2002).
85 B. Wible, T. Nicol, and N. Kraus, "Atypical brainstem representation of onset and formant structure of speech sounds in children with language-based learning problems," Biological Psychology **67**, 299–317 (2004).
86 K. L. Johnson, T. Nicol and N. Kraus, "The brainstem response to speech: A biological marker," Ear and Hearing **26**, 424–434 (2005).
87 B. Wible, T. G. Nicol, and N. Kraus, "Abnormal neural encoding of repeated speech stimuli in noise in children with learning problems," Clinical Neurophysiology **113**, 485–494 (2002).

88 K. Banai, T. Nicol, S. Zecker, and N. Kraus, “Brainstem timing: Implications for cortical processing and literacy,” J. Neurosci. **25**, 9850–9857 (2005).

89 K. Banai, J. M. Hornickel, E. Skoe, T. Nicol, S. Zecker, and N. Kraus, “Reading and subcortical auditory function,” Cerebral Cortex **19**, 2699–2707 (2009).

90 D. A. Abrams, T. Nicol, S. Zecker, and N. Kraus, “Abnormal cortical processing of the syllable rate of speech in poor readers,” J. Neurosci. **29**, 7686–7693 (2009).

91 N. Kraus, T. J. McGee, T. D. Carrell, S. G. Zecker, T. G. Nicol, and D. B. Koch, “Auditory neurophysiologic responses and discrimination deficits in children with learning problems,” Science **273**, 971–973 (1996).

92 N. M. Russo, T. G. Nicol, B. L. Trommer, S. G. Zecker, and N. Kraus, “Brainstem transcription of speech is disrupted in children with autism spectrum disorders,” Developmental Sci. **12**, 557–567 (2009).

93 N. M. Russo, S. Zecker, B. Trommer, J. Chen, and N. Kraus, “Effects of background noise on cortical encoding of speech in autism spectrum disorders,” J. Autism and Developmental Disorders **39**, 1185–1196 (2009).

94 N. M. Russo, E. Skoe, B. Trommer, T. Nicol, S. Zecker, A. Bradlow, and N. Kraus, “Deficient brainstem encoding of pitch in children with autism spectrum disorders,” Clinical Neurophysiology **119**, 1720–1731 (2008).

95 K. Banai, D. A. Abrams, and N. Kraus, “Speech evoked brainstem responses and sensory-based accounts of learning disability,” Intl. J. Audiology **46**, 524–532 (2007).

96 B. Wible, T. Nicol, and N. Kraus, “Correlation between brainstem and cortical auditory processes in normal and language-impaired children,” Brain **128**, 417–423 (2005).

97 C. M. Warrier, K. L. Johnson, E. A. Hayes, T. G. Nicol, and N. Kraus, “Learning impaired children exhibit timing deficits and training-related improvements in auditory cortical responses to speech in noise,” Experimental Brain Res. **157**, 431–441 (2004).

98 J. Cunningham, T. Nicol, S. G. Zecker, and N. Kraus, “Neurobiologic responses to speech in noise in children with learning problems: Deficits and strategies for improvement,” Clinical Neurophysiology **112**, 758–767 (2001).

99 J. Cunningham, T. Nicol, S. Zecker, and N. Kraus, “Speech-evoked neurophysiologic responses in children with learning problems: Development and behavioral correlates of perception,” Ear and Hearing **21**, 554–568 (2000).

100 G. E. Musacchia, M. Sams, and N. Kraus, “Musicianship affects acoustic and audiovisual brainstem encoding of speech and music,” in *Language and Music as Cognitive Systems*, Cambridge, UK (2007).

101 G. Musacchia, D. Strait, and N. Kraus, “Relationships between behavior, brainstem and cortical encoding of seen and heard speech in musicians and nonmusicians,” Hearing Res. **241**, 34–42 (2008).

102 D. Strait, N. Kraus, A. Parbery-Clark, and R. Ashley, “Musical experience shapes top-down auditory mechanisms: Evidence from masking and auditory attention performance,” Hearing Res. **261**, 22–29 (2010).

103 E. Skoe, C. Fabian, and N. Kraus, “The effects of musical training on subcortical processing of a missing-fundamental piano melody,” *Society for Neuroscience, Auditory Satellite (APAN)*, Chicago, IL (2009).

104 S. J. Aiken and T. W. Picton, “Envelope following responses to natural vowels,” Audiology & Neurotology **11**, 213–232 (2006).

105 H. R. Dajani, D. Purcell, W. Wong, H. Kunov, and T. W. Picton, “Recording human evoked potentials that follow the pitch contour of a natural vowel,” IEEE Transactions on Biomedical Eng. **52**, 1614–1618 (2005).

106 G. C. Galbraith, S. P. Jhaveri, and J. Kuo, “Speech-evoked brainstem frequency-following responses during verbal transformations due to word repetition,” Electroencephalography and Clinical Neurophysiology **102**, 46–53 (1997).

107 G. C. Galbraith, P. W. Arbagey, R. Branski, N. Comerci, and P. M. Rector, “Intelligible speech encoded in the human brain stem frequency-following response,” Neuroreport **6**, 2363–2367 (1995).

108 G. C. Galbraith, S. M. Bhuta, A. K. Choate, J. M. Kitahara, and T. A. Mullen, “Brain stem frequency-following response to dichotic vowels during attention,” Neuroreport **9**, 1889–1893 (1998).

109 G. C. Galbraith, E. M. Amaya, J. M. D. de Rivera, N. M. Donan, M. T. Duong, J. N. Hsu, K. Tran, and L. P. Tsang, “Brain stem evoked response to forward and reversed speech in humans,” Neuroreport **15**, 2057–2060 (2004).

110 I. Akhoun, S. Gallégo, A. Moulin, M. Ménard, E. Veuillet, C. Berger-Vachon, L. Collet, and H. Thai-Van, “The temporal relationship between speech auditory brainstem responses and the acoustic pattern of the phoneme /ba/ in normal-hearing adults,” Clinical Neurophysiology **119**, 922–933 (2008).

111 A. Krishnan, “Human frequency-following responses: representation of steady-state synthetic vowels,” Hearing Res. **166**, 192–201 (2002).

112 A. Krishnan, Y. S. Xu, J. T. Gandour, and P. A. Cariani, “Human frequency-following response: Representation of pitch contours in Chinese tones,” Hearing Res. **189**, 1–12 (2004).

[113] M. Basu, A. Krishnan, and C. Weber-Fox, "Brainstem correlates of temporal auditory processing in children with specific language impairment," Developmental Sci. **13**, 77–91 (2009).
[114] M. Steinschneider, D. Reser, C. E. Schroeder, and J. C. Arezzo, "Tonotopic organization of responses reflecting stop consonant place of articulation in primary auditory cortex (A1) of the monkey," Brain Res. **674**, 147–152 (1995).
[115] M. Steinschneider, J. Arezzo, and H. G. Vaughan, Jr., "Speech evoked activity in the auditory radiations and cortex of the awake monkey," Brain Res. **252**, 353–365 (1982).
[116] M. Steinschneider, C. E. Schroeder, J. C. Arezzo, and H. G. Vaughan, Jr., "Speech-evoked activity in primary auditory cortex: Effects of voice onset time," Electroencephalography and Clinical Neurophysiology **92**, 30–43 (1994).
[117] F. W. Ohl and H. Scheich, "Orderly cortical representation of vowels based on formant interaction," Proc. Natl. Acad. Sci. USA **94**, 9440–9444 (1997).
[118] D. Bendor and X. Q. Wang, "Cortical representations of pitch in monkeys and humans," Current Opinion in Neurobiology 16, 391–399 (2006).
[119] C. Lappe, S. C. Herholz, L. J. Trainor, and C. Pantev, "Cortical plasticity induced by short-term unimodal and multimodal musical training," J. Neurosci. **28**, 9632–9639 (2008).
[120] C. Pantev, A. Engelien, V. Candia, and T. Elbert, "Representational cortex in musicians. Plastic alterations in response to musical practice," Annals New York Acad. Sci. **930**, 300–314 (2001).
[121] C. Gaser and G. Schlaug, "Gray matter differences between musicians and nonmusicians," Annals. New York Acad. Sci. **999**, 514–517 (2003).
[122] S. Hutchinson, L. H. L. Lee, N. Gaab, and G. Schlaug, "Cerebellar volume of musicians," Cerebral Cortex **13**, 943–949 (2003).
[123] G. Schlaug, L. Jäncke, Y. X. Huang, J. F. Staiger, and H. Steinmetz, "Increased corpus-callosum size in musicians," Neuropsychologia **33**, 1047–1055 (1995).
[124] N. Suga, E. Q. Gao, Y. F. Zhang, X. F. Ma, and J. F. Olsen, "The corticofugal system for hearing: Recent progress," Proceedings Natl. Acad. Sci. of the USA **97**, 11807–11814 (2000).
[125] J. Hornickel, E. Skoe, T. Nicol, S. Zecker, and N. Kraus, "Subcortical differentiation of stop consonants relates to reading and speech-in-noise perception," Proceedings Natl. Acad. Sci. of the USA **106**, 13022–13027 (2009).
[126] A. Krishnan, "Human frequency-following responses to two-tone approximations of steady-state vowels," Audiology & Neurotology **4**, 95–103 (1999).
[127] T. Fujioka, L. J. Trainor, B. Ross, R. Kakigi, and C. Pantev, "Automatic encoding of polyphonic melodies in musicians and nonmusicians," J. Cognitive Neurosci. **17**, 1578–1592 (2005).
[128] D. A. Hodges, W. D. Hairston, and J. H. Burdette, "Aspects of multisensory perception: The integration of visual and auditory information in musical experiences," Annals New York Acad. Sci. **1060**, 175–185 (2005).
[129] L. R. Slevc and A. Miyake, "Individual differences in second-language proficiency: Does musical ability matter?," Psychological Sci. **17**, 675–681 (2006).
[130] A. Parbery-Clark, E. Skoe, and N. Kraus, "Musical experience limits the degradative effects of background noise on the neural processing of sound," J. Neurosci. **29**, 14100–14107 (2009).
[131] A. Parbery-Clark, E. Skoe, C. Lam, and N. Kraus, "Musician enhancement for speech-in-noise," Ear and Hearing **30**, 653–661 (2009).
[132] B. Chandrasekaran, J. Hornickel, E. Skoe, T. Nicol, and N. Kraus, "Context-dependent encoding in the human auditory brainstem," Neuron **64**, 311–319 (2009).
[133] M. Besson, D. Schön, S. Moreno, A. Santos, and C. Magne, "Influence of musical expertise and musical training on pitch processing in music and language," Restorative Neurology and Neurosci. **25**, 399–410 (2007).
[134] P. Tallal and N. Gaab, "Dynamic auditory processing, musical experience and language development," Trends in Neurosci. **29**, 382–390 (2006).
[135] B. Chandrasekaran and N. Kraus, "Music, noise-exclusion, and learning," Music Perception **27**, 297–306 (2010).
[136] S. Moreno and M. Besson, "Influence of musical training on pitch processing: event-related brain potential studies of adults and children," Annals New York Acad. Sci. **1060**, 93–97 (2005).
[137] N. Kraus and B. Chandrasekaran, "Music training for the development of auditory skills," Nature Reviews Neurosci. **11**, 599–605 (2010).
[138] G. Moushegian, A. L. Rupert, and R. D. Stillman, "Scalp-recorded early responses in man to frequencies in the speech range," Electroencephalography and Clinical Neurophysiology **35**, 665–667 (1973).
[139] G. C. Galbraith, "Editorial: Deficient brainstem encoding in autism," Clinical Neurophysiology **119**, 1697–1700 (2008).
[140] J. C. Smith, J. T. Marsh, and W. S. Brown, "Far-field recorded frequency-following responses: Evidence for the locus of brainstem sources," Electroencephalography and Clinical Neurophysiology **39**, 465–472 (1975).
[141] G. C. Galbraith, M. R. Threadgill, J. Hemsley, K. Salour, N. Songdej, J. Ton, and L. Cheung, "Putative measure of peripheral and brainstem frequency-following in humans," Neurosci. Lett. **292**, 123–127 (2000).
[142] G. C. Galbraith, "Two-channel brain-stem frequency-following responses to pure tone and missing fundamental stimuli," Electroencephalography and Clinical Neurophysiology **92**, 321–330 (1994).
[143] B. Chandrasekaran and N. Kraus, "The scalp-recorded brainstem response to speech: neural origins," Psychophysiology **47**, 236–246 (2010).
[144] O. S. Fowler and L. N. Fowler, *The Self-Instructor in Phrenology and Physiology: With Over One Hundred New Illustrations, Including a Chart for the Use of Practical Phrenologists* (Fowler & Wells Co., New York, 1889).
[145] E. Skoe and N. Kraus, "Auditory brainstem response to complex sounds: A tutorial," Ear and Hearing **31**, 302–324 (2010).

Nina Kraus, Ph.D., Hugh Knowles Professor, (Communication Sciences; Neurobiology and Physiology; Otolaryngology) at Northwestern University, directs the Auditory Neuroscience Laboratory (www.brainvolts.northwestern.edu). Dr. Kraus investigates the neurobiology underlying speech and music perception and learning-associated brain plasticity. She studies normal listeners throughout the lifespan, clinical populations (dyslexia; autism; hearing loss), auditory experts (musicians) and animal models. Her method of assessing the brain's encoding of sounds has been adapted as BioMARK a product that helps educators and clinicians better assess auditory function. Kraus was raised in a musically rich and linguistically diverse household. She holds degrees in Biology and Neuroscience from Swarthmore College and Northwestern University.

Trent Nicol is the manager of the Auditory Neuroscience Laboratory at Northwestern University (www.brainvolts.northwestern.edu). He is involved in all lab projects, and runs its animal research component. Over the course of his 20-year involvement with the Lab, he has been responsible for much of the instrumentation and software required for examining the brain's response to complex sounds, and has worked closely with many students who have moved on to careers in the auditory neuroscience fields. Away from the lab, he is often found hunched over a soldering iron bringing vintage radios back to life and restoring assorted pieces of obsolete vacuum tube gear.

NEUROLOGICAL BASES OF MUSICAL DISORDERS AND THEIR IMPLICATIONS FOR STROKE RECOVERY

Psyche Loui, Catherine Y. Wan, and Gottfried Schlaug
Music, Neuroimaging and Stroke Recovery Laboratories
Beth Israel Deaconess Medical Center and Harvard Medical School
Boston, Massachusetts 02215

Singing as an exercise of the auditory-motor system

Singing, or the act of producing musical sounds with the voice, is celebrated in every culture around the world. From the earliest point in infancy, humans have some knowledge of musical sounds, broadly defined—evidence for knowledge of musical attributes has been observed even in newborn infants (Winkler *et al.*, 2009). Sensitivities to pitch, key, and harmony are known to emerge from infancy to childhood (Olsho *et al.*, 1982; Trainor and Trehub, 1994) and have been reported in many other cultures (Castellano *et al.*, 1984; Krumhansl *et al.*, 2000; Trehub *et al.*, 2008). Because of its prevalence among humans, the ability to make music has been posited as an innate human ability (Peretz, 2006).

"Singing, or the act of producing musical sounds with the voice, is celebrated in every culture around the world."

Singing requires the coordination of auditory and motor networks and involves the perception and production of pitch and rhythm. People who have problems with singing, i.e., tone-deaf people, provide an interesting model for studying brain networks involved in singing and how they might overlap with networks for speaking abilities. This overlap of neural resources recruited in singing and speaking is useful in therapeutic applications, where the loss of language function (a condition known as aphasia) can be rehabilitated using a treatment program known as Melodic Intonation Therapy (Schlaug *et al.*, 2008; Norton et al., 2009; Schlaug *et al.*, 2009). In this article, we will review current research in our lab on singing: what the ability entails, why some individuals lack singing ability, and how singing can be used to improve the well-being of those afflicted by neurological disorders.

Tone-deafness as a musical disorder

Despite the pervasive evidence for musical ability (especially singing ability) in all cultures, some individuals have an unusual lack of musical skill, especially in the perception and production of pitch: a condition known as congenital amusia, also known as tone-deafness. Tone-deaf individuals can be identified among others by using the standardized perceptual test known as Montreal Battery for the Evaluation of Amusia (MBEA), (Peretz *et al.*, 2003). The MBEA consists of pairs of melodies that are either the same or different in melodic or rhythmic content; the test taker's task is to decide whether the pairs of melodies are the same or different, and individuals who score below a cutoff are labeled as amusic. In addition to the MBEA, we employ a psychophysical listening test that finds the threshold at which pitch differences can reliably be detected. A version of this test can now be taken online at www.musicianbrain.com. Using this test, individuals with a pitch-discrimination threshold of more than a semitone are considered tone-deaf (Foxton *et al.*, 2004; Loui *et al.*, 2008). In addition to these perceptual tests, tone-deaf individuals are identifiable by their inability to sing in tune.

The majority of tone-deaf individuals are unaware of their inability to perceive pitches, but only of their inability to sing—perhaps resulting from being discouraged from singing by those around them (Cuddy *et al.*, 2005). While conventional wisdom might suggest that hearing pitches and producing them are intricately linked abilities, in previous studies we had identified that the abilities to perceive and to produce pitches are not necessarily the same amongst all individuals: in a study in published in 2008, we observed that tone-deaf individuals, who cannot consciously perceive pitch differences smaller than a semitone, can paradoxically *produce* these pitch intervals in the right direction (Loui *et al.*, 2008). Furthermore, the threshold difference at which tone-deaf subjects can reliably produce pitch differences is smaller than the threshold difference at which they can reliably perceive pitch differences, suggesting that tone-deaf individuals have the unconscious ability to produce pitches even in the absence of conscious pitch perception, resulting in a mismatch between pitch perception and production abilities. Perhaps because of these residual pitch production abilities even in the absence of intact pitch perception, tone-deaf individuals are generally able to speak normally. There are, however, several reports that the perception of intonation in speech is disrupted in tone-deaf individuals (Patel *et al.*, 2005; Patel *et al.*, 2008), which raises two interesting questions. First, how do tone-deaf individuals speak and understand speech in tonal language cultures? And a second related question—what, if any, compensatory neural mechanisms might the tone-deaf individuals be using to produce normal speech? Several research projects in our lab and others are currently trying to answer these questions.

Neuroimaging of tone-deafness implicates auditory-motor regions in frontal and temporal lobes

In addition to the behavioral studies described above, neuroimaging research is now underway to examine the neural underpinnings of pitch perception and production, specifically in tone-deaf individuals. Magnetic resonance imaging (MRI) studies have explored the neuroanatomical basis of tone-deafness. Studies looking at voxel-based morphometry and cortical thickness (Hyde *et al.*, 2006; Hyde *et al.*, 2007; Mandell *et al.*, 2007), two measures of structure of grey matter in the brain, found that tone-deaf individuals possess differences in the superior temporal and inferior frontal areas. These differences were reported as being specific to the right hemisphere by Hyde *et al.*. (2007), but were found to be involving more left fronto-temporal regions by Mandell *et al.*. (2007). The hemispheric differences between the effects observed may arise from different samples of subjects, different data analysis techniques in analyzing structural neuroimaging data, and different thresholding techniques employed in the published studies. In particular, left-hemisphere differences were observed using the dependent variable of grey matter signal, whereas right-hemisphere differences were observed using the dependent variable of cortical thickness. These two variables may be capturing different biological bases of neuronal structure that are sensitive to different between-subject factors in the two hemispheres.

Regardless of the differences between image analysis methods, the mounting body of structural neuroimaging literature on tone-deafness suggests that the inferior frontal gyrus and the superior part of the posterior temporal lobe (including the superior and middle temporal gyri) are consistently abnormal in tone-deaf individuals. This is further corroborated by functional magnetic resonance imagining (fMRI) data, which also identified the right superior temporal regions and right inferior frontal gyrus as being deficient in functional activation for tone-deaf individuals relative to controls (Hyde *et al.*, 2010). The general locations of the inferior frontal region (red) and superior temporal lobe (blue) are shown on a model brain in Fig. 1a.

One possible explanation for the simultaneously observed differences in frontal and temporal regions is that these two cortical regions are connected by a highway of white matter that runs between them (shown in yellow in Fig. 1a). Abnormal or deficient development in this white matter pathway among tone-deaf individuals can lead to simultaneous anomalies in the endpoints of this pathway. Alternatively, an abnormality in one of the endpoints in this network may affect the other endpoint and the tract that connects the endpoints. These hypotheses hinge on being able to visualize the white matter pathway, and white matter in the brain is best identifiable using Diffusion Tensor Imaging (DTI), a structural magnetic resonance imaging (MRI) method that uses diffusion properties of water to infer structural properties of connections in the brain (for a review, see Basser and Jones, 2002). In particular, the white matter pathway that connects the inferior frontal areas with superior temporal areas is known as the arcuate fasciculus (illustrated in Figure 1b). Patients with isolated damage to the left arcuate fasciculus (e.g., due to stroke, tumor, or traumatic brain injury) are typically unable to repeat words in a condition known as conduction aphasia, which will be revisited later in this article.

To test the hypothesis that the arcuate fasciculus is involved in tone-deafness, we conducted a diffusion tensor imaging study in our laboratory. Twenty individuals were tested for pitch discrimination and pitch production thresholds and underwent diffusion tensor imaging. The endpoints of the arcuate fasciculus, i.e., superior temporal and inferior frontal regions in each hemisphere of each brain, were highlighted as regions of interest. All connections between the regions of interest in each hemisphere were identified using a tractography algorithm that connects successive voxels with similar paths of preferential diffusion direction, thus identifying the arcuate fasciculus.

Figure 2 shows the arcuate fasciculus in both left and right hemispheres identified in a normal individual (Fig. 2a) and a tone-deaf individual (Fig. 2b). As is evident by comparing the two figures, the tone-deaf individual possesses much less fiber volume in the arcuate fasciculus. In a group study (n = 20), the arcuate fasciculus was found to be diminished in volume among tone-deaf individuals compared to matched controls. Furthermore, the pitch perception and pitch production thresholds were positively correlated with the volume of the arcuate fasciculus (Loui *et al.*, 2009). These differences between tone-deaf and non-tone-deaf brain structures suggest that the arcuate fasciculus plays an important role in pitch perception and production. (Fig. 2).

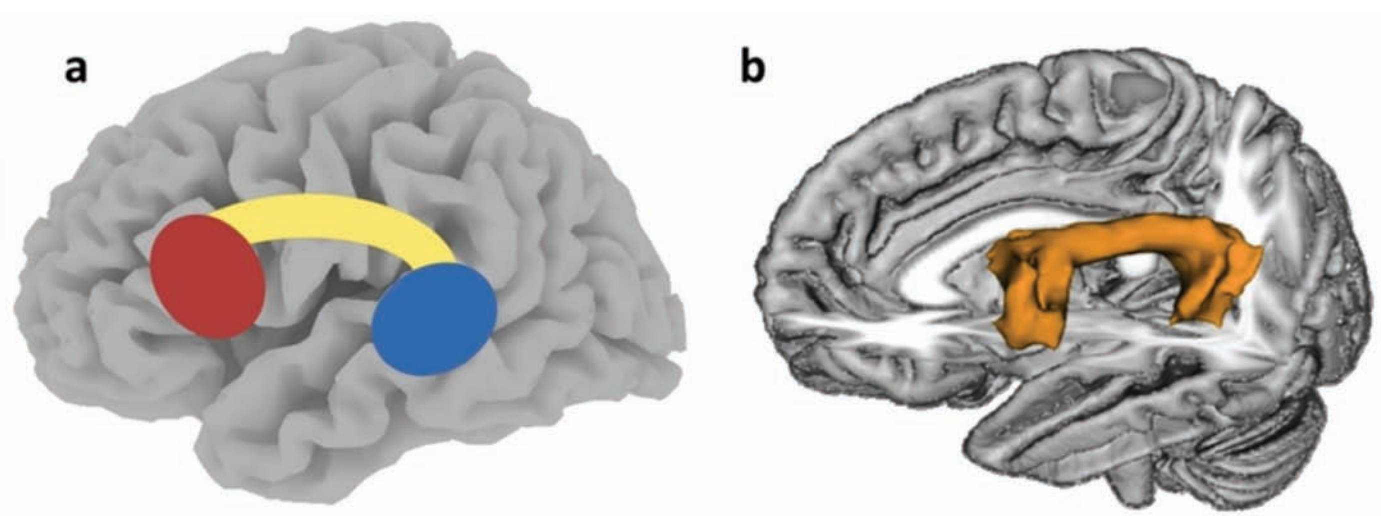


Fig. 1. a) Schematic of basic brain network involved in singing. Red and blue indicate locations of inferior frontal and superior temporal areas; yellow indicates white matter that runs between the temporal and frontal lobes. b) Results of diffusion tensor tractography showing the arcuate fasciculus overlaid on a standard brain template. Orange indicates the arcuate fasciculus, the white matter pathway that connects the inferior frontal areas with superior temporal areas.

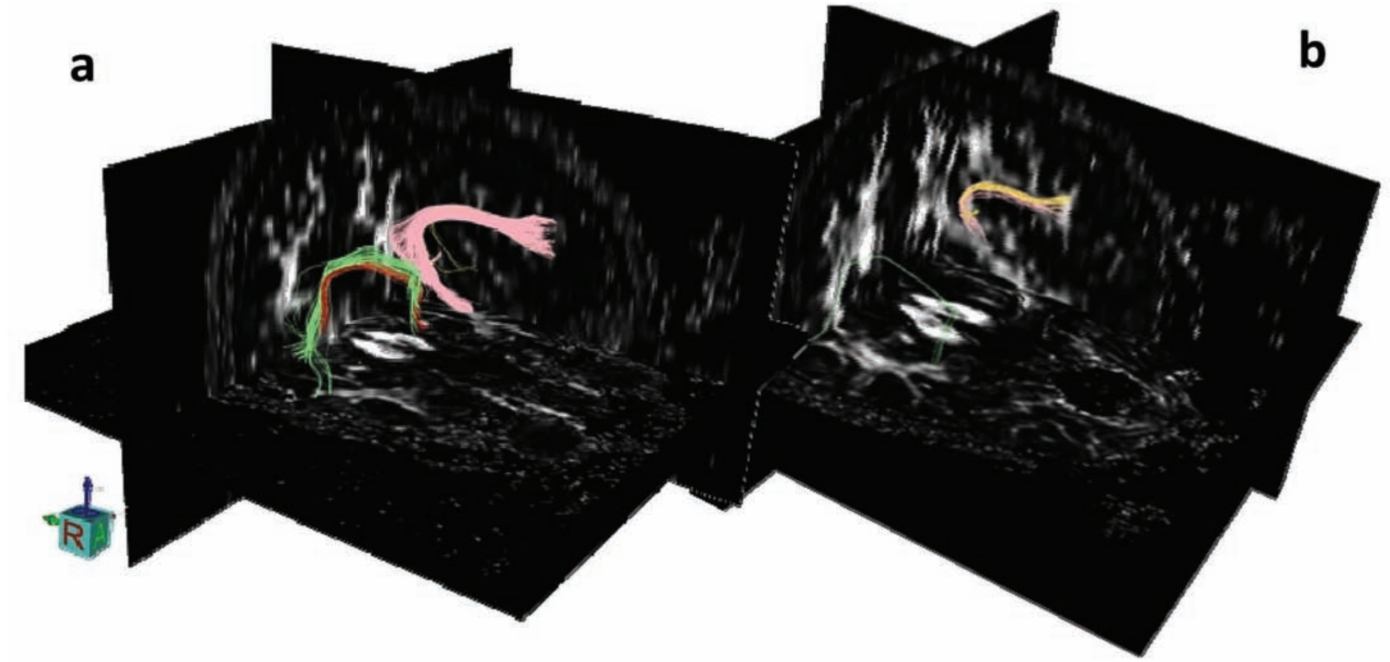


Fig. 2. Tractography results from a) a non-tone-deaf individual, and b) a tone-deaf individual, showing distinct branches of the arcuate fasciculus. Pink and yellow are tracts identified in the left hemisphere, whereas red and green are tracts identified in the right hemisphere.

Brain-stimulation affects pitch production, simulating tone-deafness

Although the neuroimaging results are striking and robust, they provide only correlational evidence rather than causal evidence for superior temporal regions, inferior frontal regions, and the arcuate fasciculus as a pitch perception and production network. To show that the grey matter regions in frontal and temporal regions are necessary for accurate pitch production, an experimental intervention is required where the hypothetical pitch production network is disrupted in a controlled manner. To this end, a recent study in our lab (Loui *et al.*, 2010) tested the causal role of superior temporal and inferior frontal gyri in pitch production using noninvasive brain stimulation as an intervention method. In this study, we measured pitch matching behavior before and after delivering temporary stimulation to superior temporal and inferior frontal regions using transcranial direct current stimulation (tDCS). TDCS is a noninvasive brain stimulation technique that modulates the firing rate of neurons by low-current stimulation applied through electrodes attached to the surface of the scalp (for a review, see Wagner *et al.*, 2007). Previous studies have shown selective but temporary impairment of cortex underlying the targeted stimulation in motor and cognitive tasks (Vines *et al.*, 2006a; Vines *et al.*, 2006b; Cerruti and Schlaug, 2008). Pitch production accuracy, as measured by the mean deviation between produced frequency and target frequency, was disrupted following noninvasive brain stimulation, with effects being most robust after stimulation to the left inferior frontal gyrus. By inducing disruptions in pitch production behavior through the reverse-engineering approach of noninvasive brain stimulation, these results are important in establishing a causal role of the temporal and frontal brain network in pitch production. The observed results in pitch matching parallel results obtained from tone-deaf individuals, who show obvious impairments in pitch matching (Loui *et al.*, 2008; Dalla Bella *et al.*, 2009; Hutchins *et al.*, 2010). The brain-stimulation data suggest that accurate pitch production requires a distributed cortical network including superior temporal and inferior frontal areas.

Singing changes autonomic and central nervous systems—brain differences in trained singers

Pitch production is only one of several crucial basic components of singing. In the central nervous system, singing requires multiple stages of perceptual, cognitive, and motor operations. First, the brain must form an accurate mental representation of the target sounds to be produced. Then, a motor plan that matches the target mental representation has to be selected and executed. After the motor plan is executed, the auditory system must perceive feedback from one's own voice so that vocal output can be fine-tuned in real time. These mental operations must be performed on both the rhythmic and melodic components of music, which are hypothesized to have different representations in long-term memory (Hebert and Peretz, 1997), but both components are important for singing or for music making more generally.

Due to the requirements that singing places on the central nervous system, there is mounting evidence that vocal training changes the brain in structure and function. In a functional MRI study, experienced opera singers showed differences in functional activation in the inferior parietal lobes and bilateral dorsolateral prefrontal cortex compared to non-singers (Kleber *et al.*, 2009). In a DTI study in our lab (Halwani *et al.*, submitted 2010), we compared the arcuate fasciculus of experienced singers against instrumental musicians with similar durations of musical training. Figure 3 shows group results from this study, with averaged arcuate fasciculi in 10 singers in Fig. 3a and 10 control musicians in Fig. 3b. As the figure shows, singers possess larger tract volume and lower fractional anisotrophy values in the left arcuate fasciculus relative to other (instrumental) musicians, suggesting that experience-dependent plasticity is at work in shaping both neural structure and function of singers, especially in the auditory-motor networks of the brain. Singing affects a network that is robust above and beyond the effects of other types of musical training. This "singing-related" network, possibly resulting from the long-term engagement of the vocal apparatus, may also be tied to nonmusical vocal functions such as speech. (see Fig. 3)

Study of tone-deafness has implications for the rehabilitation of speech disorders

As presented above, the network of brain regions that is deficient in tone-deaf individuals and hyper-developed in singers includes the superior temporal lobe (superior temporal gyrus and middle temporal gyrus) and the inferior frontal lobe (inferior frontal gyrus). This network is not only involved in pitch production, but also plays a crucial role in speech and language processing. Indeed, numerous studies have shown that there are overlapping responses to music and language stimuli in the brain. For example, fMRI studies have reported activation of Broca's area during music perception tasks (e.g., Koelsch *et al.*, 2002; Tillmann *et al.*, 2003), during active music tasks such as singing (e.g., Ozdemir *et al.*, 2006), and even when participants imagined playing an instrument (e.g., Meister *et al.*, 2004; Baumann *et al.*, 2007). Moreover, a common network appears to support the sensori-motor components for both speaking and singing (e.g., Pulvermuller, 2005; Ozdemir *et al.*, 2006; Kleber *et al.*, 2009). Given the shared neural correlates between music and language, as well as our understanding of the mechanisms underlying the deficits of tone-deaf individuals, researchers have begun to evaluate the potential utility of music-based interventions in the treatment of neurological disorders. This field of research is motivated by a large body of research demonstrating that engaging in musical activities has dramatic effects on plasticity in the developing brain as well as in the mature brain (Fujioka *et al.*, 2006; Lahav *et al.*, 2007; Hyde *et al.*, 2009). Music-based interventions have the potential to facilitate this recovery process of the injured brain as well as the development of language in children with developmental disorders. We provide below, two examples of such an application: one in stroke patients with aphasia, and another in nonverbal children with autism.

Music-based intervention in the treatment of aphasia

Aphasia is a common complication of stroke that results in the loss of ability to produce and/or comprehend language. The nature and severity of language dysfunction depends on the location and extent of the brain lesion. Patients who are non-fluent usually have a lesion in the left frontal lobe involving, among others, the left posterior inferior frontal region (Broca's area). These non-fluent patients often have the ability to comprehend the speech of others, but they also have impairments in the production of words or propositional speech. The consensus is that there are two routes to recovery from a stroke-induced aphasia. In patients with small lesions in the left hemisphere, there tends to be recruitment of both left-hemispheric, perilesional cortex with variable involvement of right-hemispheric homologous regions during the recovery process. In patients with large left-hemispheric lesions involving language-related regions of the fronto-temporal lobes, the only path to recovery may be through recruitment of homologous language and speech-motor regions in the right hemisphere (Schlaug *et al.*, 2010). For patients with large lesions that cover the language-relevant regions on the left, therapies that specifically engage or stimulate the homologous right-hemispheric regions have the potential to facilitate the language recovery process beyond the limitations of natural recovery. Melodic Intonation Therapy (MIT) is one music-based intervention that might be predestined in that approach—it may improve speech production and brain changes in patients with large left hemisphere lesions that result in severe non-fluent aphasia. MIT is an intensive intervention that involves practicing

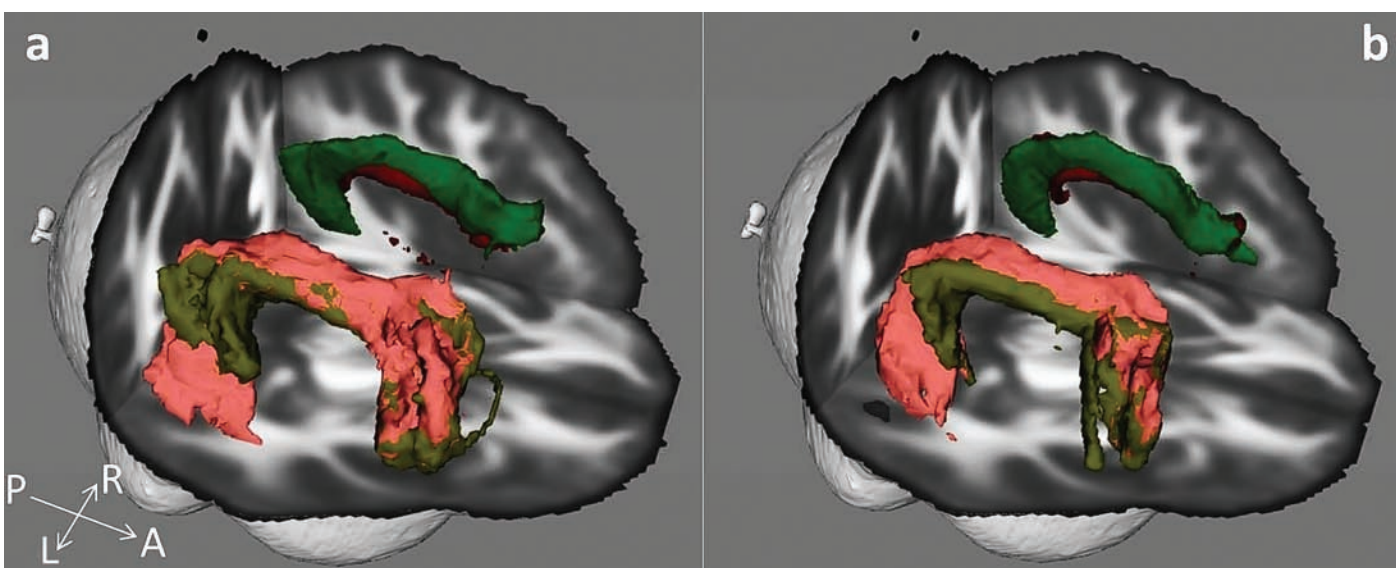


Fig. 3. Tractography results from averaged groups of a) 10 singers and b) 10 control musicians, showing the arcuate fasciculus. Pink and olive green are tracts identified in the left hemisphere, whereas red and green are tracts identified in the right hemisphere.

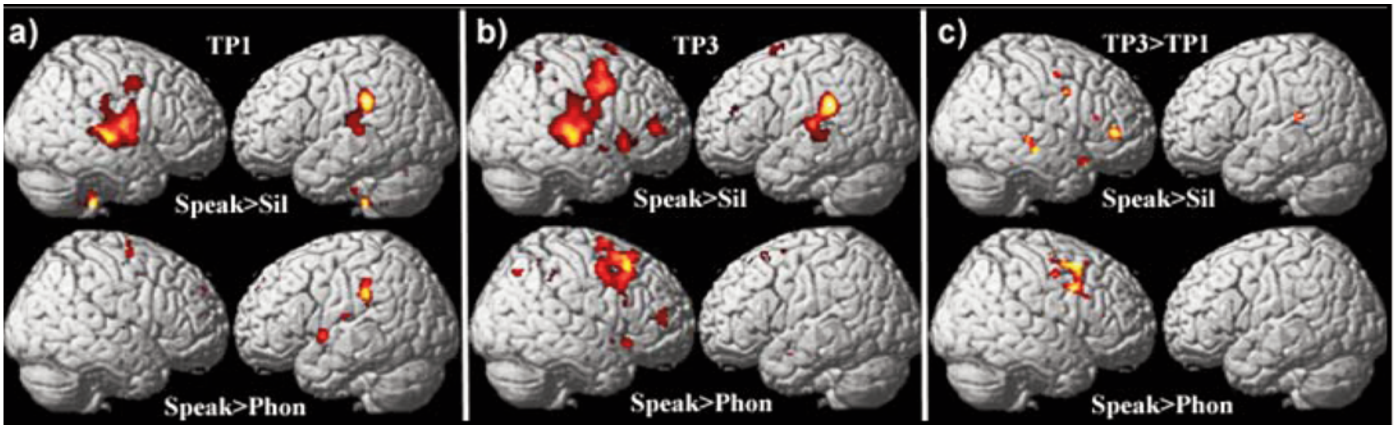


Fig. 4. Significant functional magnetic resonance imaging (fMRI) activations in a single patient before and after therapy. a) Activations before therapy. b) Activations after therapy. c) A direct comparison between after-therapy and before-therapy activations. The top panels show left and right brain activation during overt speaking contrasted with a silent control. The bottom panels show brain activation during overt speaking contrasted with the control task of vowel production. All contrasts are superimposed on a spatially standardized normal brain template and use a threshold at a level of $p < 0.05$ (statistically corrected for family-wise error). The color codes represent different magnitudes of activation: stronger activations are indicated in yellow. Reprinted with permission from Schlaug *et al.* (2010).

a series of words or phrases using slow, pitched vocalization or singing in combination with rhythmic tapping of the left hand (Albert *et al.*, 1973; Norton *et al.*, 2009). The effectiveness of MIT has been demonstrated by behavioral improvements in naming (Bonakdarpour *et al.*, 2000; Sparks *et al.*, 1974) and in articulation and phrase production (Wilson *et al.*, 2006) after treatment. A recent study involving two patients examined the benefit of MIT on transfer of language skills to untrained contexts (Schlaug *et al.*, 2008). In that study, which involved 75 daily sessions of 90 minutes, the extent of this improvement was far greater for the patient who underwent MIT compared to the one who underwent the control therapy. Furthermore, neuroimaging of this patient showed that MIT results in increased activation in a right-hemisphere network involving the premotor, inferior frontal, and temporal lobes (Schlaug *et al.*, 2008), as well as increased fiber number and volume of the arcuate fasciculus in the right hemisphere (Schlaug *et al.*, 2009). Critically, the patient treated with a non-intonation-based speech therapy showed smaller right hemisphere changes and more left hemisphere changes. These findings demonstrate that intensive training involving through singing, applied over a longer period of time in chronic stroke patients, can induce functional and structural brain changes. These changes are related to speech output improvements in patients suffering from aphasia.

Facilitating recovery from aphasia by engaging predominantly the right hemisphere of the brain

The traditional explanation for the dissociation between speaking and singing in patients with aphasia is the presence of two routes for word articulation: one for spoken words through the brain's left hemisphere, and a separate route for sung words that uses either the right or both hemispheres. However, research indicates that there is a bi-hemispheric role in the execution and sensorimotor control of vocal production for both speaking and singing (Guenther *et al.*, 1998; Jeffries *et al.*, 2003; Brown *et al.*, 2004; Bohland and Guenther, 2006; Ozdemir *et al.*, 2006), typically with a left-lateralization for speaking. It has been shown that tasks that emphasize spectral information over temporal information elicit more right- than left-hemispheric activation (Zatorre and Belin, 2001; Meyer *et al.*, 2002). Similarly, patients with right-hemisphere lesions have greater difficulty with global processing (e.g., melody and contour processing) compared to those with left-hemisphere lesions (Peretz, 1990; Schuppert *et al.*, 2000). Thus, it is possible that the melodic element of MIT engages the right hemisphere, particularly the right temporal lobe, more so than therapies that do not make use of pitch or melody. To date, only a handful of brain imaging studies has shed light on the possible neural mechanisms underlying language recovery following MIT. One interpretation is that MIT engages the expressive language areas in the right hemisphere. Alternatively, MIT could exert its effect either by unmasking existing music/language connections in both hemispheres, or by engaging preserved language-capable regions in either or both hemispheres. Since MIT incorporates both the melodic and rhythmic aspects of music (Albert *et al.*, 1973; Sparks *et al.*, 1974; Sparks and Holland, 1976; Helm-Estabrooks, 1989; Cohen and Masse, 1993; Boucher *et al.*, 2001; Norton *et al.*, 2009), it may be unique in its potential to engage not only the right, but both hemispheres.

Data from our laboratory indicate that patients who undergo an intensive course of MIT show functional and structural brain changes in their right hemispheres (Schlaug *et al.*, 2008; Schlaug *et al.*, 2009). Figure 4 shows significant fMRI activations in a single patient before and after therapy (Fig. 4a: before therapy; Fig. 4b: after therapy). The top panels show left and right brain activation during overt speaking contrasted with a silent control. The bottom panels show brain activation during overt speaking contrasted with the control task of vowel production. All contrasts are superimposed on a spatially standardized normal brain template and thresholded at a level of $p < 0.05$ (statistically corrected for family-wise error.) Furthermore, a direct voxel-by-voxel comparison of the two acquisitions is shown in Fig. 4c. The color codes represent different magnitudes of activation: stronger activations are indicated in yellow. As shown in this figure, the most significant activations in these patients during a speaking task were located in the right hemisphere. More importantly, the magnitude of this activation was greater after the patient was treated with MIT, indicating therapy-induced brain changes. (see Fig. 4)

In terms of structural changes, our preliminary data show modifications of the right arcuate fasciculus following MIT. As described in the preceding section, the arcuate fasciculus, a fiber tract that connects the superior temporal lobe with the posterior inferior frontal gyrus, is very important for auditory-motor mapping and plays a crucial role in language development (Glasser and Rilling, 2008; Rilling *et al.*, 2008). Figure 5 shows a diffusion tensor imaging study of a patient who underwent MIT. The treatment-induced increase is evident when the before-therapy (Fig. 5a) and after-therapy (Fig. 5b) images are compared against each other: the arcuate fasciculus is larger in volume after therapy. We believe that the intensity of MIT may be important for facilitating plasticity and remodeling of this fiber tract (Schlaug *et al.*, 2009). (se Fig. 5)

Music-based intervention in the treatment of nonverbal children with autism

In addition to facilitating the language recovery in stroke patients, music-based interventions can also be used to induce plasticity and to restore cognitive functions in children with developmental disorders, such as Autism Spectrum Disorders (ASD). ASD affects 1 in 110 children, and one of its core diagnostic features relates to impairments in language and communication. It has been estimated that up to 25% of individuals with ASD lack the ability to communicate with others using speech sounds (www.autismspeaks.org). Despite their verbal communication deficits, children with ASD enjoy auditory-motor activities such as making music through singing or playing an instrument (Trevarthen *et al.*, 1996). In addition, they often display enhanced music and auditory-perception abilities (e.g., Heaton, 2003). Such positive responses to music suggest that an intonation- or singing-based intervention may have great therapeutic potential by tapping into an activity that these children enjoy.

At present, there are no established techniques that reliably produce improvements in speech output in nonverbal children with ASD (Francis, 2005). Two published case studies have shown that an intonation or singing-based technique has great potential. One study used an adapted version of MIT involving intoned questions and statements (Miller and Toca, 1979). Another study reported using pitch matching and singing to encourage vocalizations, which eventually led to the articulation of words (Hoelzley, 1993). Although the results of these single case studies are encouraging, the efficacy of these methods have to be tested in a controlled design which would allow us to determine whether these approaches can be generalized to a broader population of affected individuals, and whether effects in the trained words/phrases transfer to untrained items.

Our laboratory has recently developed a similar intonation-based intervention, termed Auditory-Motor Mapping Training (AMMT), to help nonverbal children with ASD develop verbal expressive language (Wan *et al.*, 2010a; Wan *et al.*, 2010b). This type of training builds upon the seemingly inherent musical strengths that have been observed in children with ASD. Furthermore, AMMT is an adaptation of an intonation-based technique (MIT) that has been successful in facilitating speech output in patients with Broca's aphasia. As described earlier, recent studies have shown that compared to speaking, singing engages a bilateral fronto-temporal network in the brain, and that this network contains some components of the mirror neuron system (Brown *et al.*, 2004; Ozdemir *et al.*, 2006). Some researchers have argued that the communication deficits associated with ASD may be caused by a dysfunction of the mirror neuron system (e.g., Hadjikhani, 2007; Iacoboni and Dapretto, 2006). Combining sounds with actions, in particular, could play an important role in the engagement and repair of the "hearing-doing" (auditory-motor mapping) network that may be dysfunctional in autism.

The application of MIT to the treatment of autism requires some procedural modifications from its original form in the treatment of aphasia. Our AMMT intervention involves repeated trials of bimanual sound-motor mapping through the use of tuned drums (Wan *et al.*, 2010). For children with autism, it is important to first establish a comfortable treatment environment. The session includes a vocalization procedure, during which the child is encouraged to vary the intensity and length of speech sounds. A series of picture

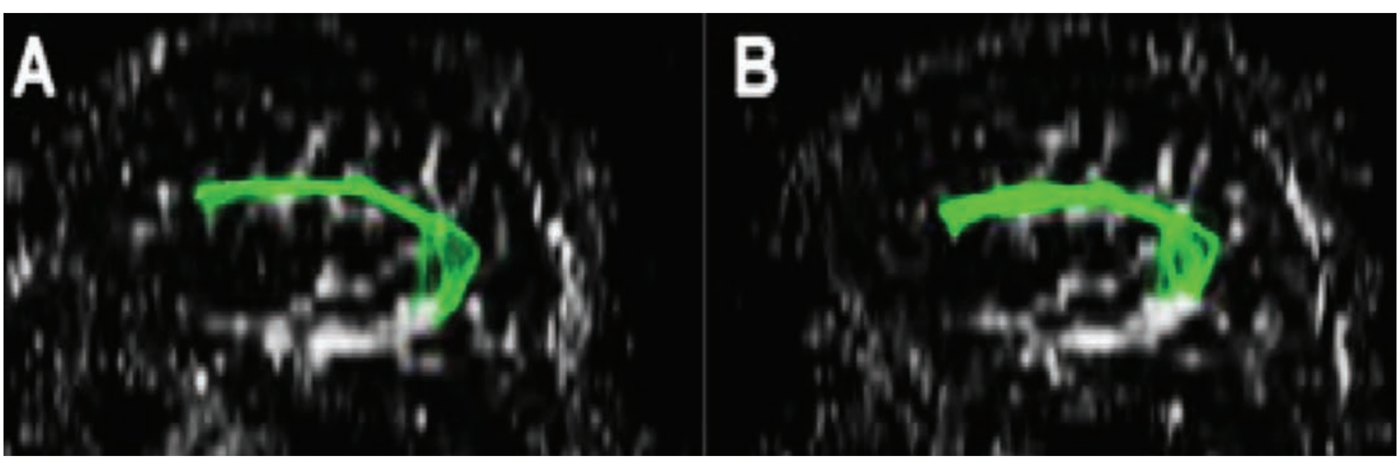


Fig. 5. Diffusion tensor images of a patient who received melodic intonation therapy (MIT), showing the arcuate fasciculus in green. a) Before therapy. b) After therapy. Reprinted with permission from Schlaug *et al.* (2010).

stimuli is then presented using a procedure adapted from MIT (see Norton *et al.*, 2009). These stimuli include common objects, actions, and social phrases. In addition to intonation, a key component of AMMT is the use of a set of tuned drums to facilitate sound-motor mapping. The therapist introduces the target words or phrases by intoning (singing) the words on two pitches and playing the drums at the same time. As in the MIT protocol, the child progresses from passive listening, to unison singing, to partially-supported singing, to immediate repetition, and finally to producing the target word or phrase on their own.

Testing is currently underway in our laboratory to examine the efficacy of AMMT in facilitating speech output in nonverbal children with ASD. Because AMMT enhances interactions between the auditory and motor systems, it may represent an effective therapeutic strategy through which individuals with autism can develop their communication skills.

Concluding remarks

In the present article, we have reviewed a substantial body of behavioral and neuroscience studies on singing, including investigations of trained singers, tone-deaf individuals who have trouble singing, and the therapeutic effects of singing on recovery of language functions in patients with severe non-fluent aphasia and children with non-verbal forms of autism. Singing is a set of abilities enabled by the auditory-motor system, involving continuous perception, production, feedback and feedforward control mechanisms, and mental representation of vocal sounds. Because of the complex requirements that singing places on the brain, the study of disorders in singing abilities provides a useful model for the neural basis of singing. Tone-deafness, which is phenotypically best described as an inability to sing in tune, helps us understand how the auditory-motor system functions: in particular, knowledge regarding how pitch changes in speech and music engage similar brain networks is useful for informing the development of therapies for other neurological disorders.

Singing represents a promising therapeutic tool in a variety of neurological disorders. Music-based interventions are useful for recovery from aphasia: Melodic Intonation Therapy (MIT) effectively slows down regular speech into pitched vocalizations that engage right-hemisphere-dominant functions, while simultaneously engaging rhythm networks via left-hand rhythmic tapping. Functional MRI and DTI studies have highlighted several possible mechanisms that may underlie the efficacy of singing in ameliorating impairments in speech production in aphasic patients, with the effects of therapy being most dominant in auditory-motor networks in the right hemisphere. A similar intonation-based intervention, termed Auditory-Motor Mapping Training (AMMT), has been designed with the added benefit of capitalizing on relatively intact musical functioning of nonverbal children with autistic spectrum disorders with the end goal of helping them develop verbal expressive language.

Although it might be difficult to test the contribution of all of the variables that are incorporated into an intervention on speech motor output, it is important to test the efficacy of any new experimental intervention against a controlled or established intervention in a randomized, well-controlled trial. Equally important is the basic understanding of the neural mechanisms underlying singing and auditory-motor mapping. Elucidating these mechanisms will allow us to tailor the interventions, to select the most appropriate patients for efficient interventions, and to make predictions about recovery.**AT**

References

Albert, M. L., Sparks, R. W., and Helm, N. A. (**1973**). "Melodic intonation therapy for aphasia," Archives of Neurology **29**, 130–131.

Basser, P. J., and Jones, D. K. (**2002**). "Diffusion-tensor MRI: theory, experimental design and data analysis – A technical review," NMR in Biomedicine **15**, 456–467.

Baumann, S., Koeneke, S., Schmidt, C.F., Meyer, M., Lutz, K., and Jancke L.A. (**2007**). "A network for audio-motor coordination in skilled pianists and non-musicians," Brain Res. **1161**, 65–78.

Bohland, J. W., and Guenther, F. H. (**2006**). "An fMRI investigation of syllable sequence production," NeuroImage **32**, 821–841.

Bonakdarpour, B., Eftekharzadeh, A., Ashayeri, H. (**2000**). "Preliminary report on the effects of melodic intonation therapy in the rehabilitation of Persian aphasic patients," Iranian J. Medical Sci. **25**, 156–60.

Boucher, V., Garcia, L. J., Fleurant, J., Paradis, J. (**2001**). "Variable efficacy of rhythm and tone in melody-based interventions: implications for the assumption of a right-hemisphere facilitation in nonfluent aphasia," Aphasiology **15**, 131–149.

Brown, S., Martinez, M. J., Hodges, D. A., Fox, P. T., and Parsons, L. M. (**2004**). "The song system of the human brain," Brain Res. Cognition Brain Res. **20**, 363–375.

Castellano, M. A., Bharucha, J. J., and Krumhansl, C. L. (**1984**). "Tonal hierarchies in the music of north India.," J. Experimental Psychology: General **113**, 394–412.

Cerruti, C., and Schlaug, G. (**2008**). "Anodal transcranial direct current stimulation of the prefrontal cortex enhances complex verbal associative thought," J. Cognitive Neurosci. **21**, 1980–1987.

Cohen, N. S., and Masse, R. (**1993**). "The application of singing and rhythmic instruction as a therapeutic intervention for persons with neurogenic communication disorders," J. Music Therapy **30**, 81–99.

Cuddy, L. L., Balkwill, L. L., Peretz, I., and Holden, R. R. (**2005**). "Musical difficulties are rare: a study of 'tone deafness' among university students," Annals New York Acad. Sci. **1060**, 311–324.

Dalla Bella, S., Giguere, J. F., and Peretz, I. (**2009**). "Singing in congenital amusia," J. Acoust. Soc. Am. **126**, 414–424.

Foxton, J. M., Dean, J. L., Gee, R., Peretz, I., and Griffiths, T. D. (**2004**). "Characterization of deficits in pitch perception underlying 'tone deafness'," Brain **127**, 801–810.

Francis, K. (**2005**). "Autism interventions: a critical update," Developmental Medicine and Child Neurology **47**, 493–499.

Fujioka, T., Ross, B., Kakigi, R., Pantev, C., and Trainor, L. J. (**2006**). "One year of musical training affects development of auditory cortical-evoked fields in young children," Brain **129**, 2593–2608.

Glasser, M. F., and Rilling, J. K. (**2008**). "DTI tractography of the human brain's language pathways," Cerebral Cortex 11, 2471–2482.

Guenther, F. H., Hampson, M., and Johnson, D. (**1998**). "A theoretical investigation of reference frames for the planning of speech movements," Psychological Rev. **105**, 611–633.

Hadjikhani, N. (**2007**). "Mirror neuron system and autism," in P. C. Carlisle (Ed.), *Progress in Autism Research* (Nova Science Publishers, Hauppauge, NY) 151–166

Halwani, G. F., Loui, P., and Schlaug, G. (**2010**). "Enhanced vocal-motor networks in singers as revealed by diffusion-tensor imaging," submitted.

Heaton, P. (**2003**). "Pitch memory, labelling and disembedding in autism," J. Child Psychology and Psychiatry and Allied Disciplines **44**, 543–551.

Hebert, S., and Peretz, I. (**1997**). "Recognition of music in long-term memory: Are melodic and temporal patterns equal partners?," Memory and Cognition **25**, 518–533.

Helm-Estabrooks, N., Nicholas, M., and Morgan, A. (**1989**). *Melodic Intonation Therapy* (Pro-Ed, Austin).

Hoelzley, P. D. (**1993**). "Communication potentiating sounds: Developing channels of communication with autistic children through psychobiological responses to novel sound stimuli," Canadian J. Music Therapy **1**, 54–76.

Hutchins, S., Zarate, J. M., Zatorre, R. J., and Peretz, I. (**2010**). "An acoustical study of vocal pitch matching in congenital amusia," J. Acoust. Soc. Am. **127**, 504–512.

Hyde, K. L., Lerch, J. P., Zatorre, R. J., Griffiths, T. D., Evans, A. C., and Peretz, I. (**2007**). "Cortical thickness in congenital amusia: When less is better than more," J. Neurosci. **27**, 13028–13032.

Hyde, K. L., Zatorre, R. J., Griffiths, T. D., Lerch, J. P., and Peretz, I. (**2006**). "Morphometry of the amusic brain: A two-site study," Brain **129**, 2562–2570.

Hyde, K. L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A. C., and Schlaug, G. (**2009**). "Musical training shapes structural brain development," J. Neurosci. **29**, 3019–3025.

Hyde, K. L., Zatorre, R. J., and Peretz, I. (**2010**). "Functional MRI evidence of an abnormal neural network for pitch processing in congenital amusia," Cerebral Cortex, doi:10.1093/cercor/bhq094

Iacoboni, M., and Dapretto, M. (**2006**). "The mirror neuron system and the consequences of its dysfunction," Nature Reviews Neurosci. **7**, 942–951.

Jeffries, K. J., Fritz, J. B., and Braun, A. R. (**2003**). "Words in melody: An H(2)15O PET study of brain activation during singing and speaking," Neuroreport **14**, 749–754.

Kleber, B., Veit, R., Birbaumer, N., Gruzelier, J., and Lotze, M. (**2009**). "The brain of opera singers: Experience-dependent changes in functional activation," Cerebral Cortex **20**, 1144–1152.

Koelsch, S., Gunter, T. C., von Cramon, D. Y., Zysset, S., Lohmann, G., and Friederici, A. D. (**2002**). "Bach speaks: A cortical 'language-network' serves the processing of music," Neuroimage **17**, 956–966.

Krumhansl, C. L., Toivanen, P., Eerola, T., Toiviainen, P., Jarvinen, T., and Louhivuori, J. (**2000**). "Cross-cultural music cognition: Cognitive methodology applied to North Sami yoiks," Cognition **76**, 13–58.

Lahav, A., Saltzman, E., and Schlaug, G. (**2007**). "Action representation of sound: Audiomotor recognition network while listening to newly acquired actions," J. Neurosci. **27**, 308–314.

Loui, P., Alsop, D., and Schlaug, G. (**2009**). "Tone-deafness: A disconnection syndrome?," J. Neurosci. **29**, 10215–10220.

Loui, P., Guenther, F. H., Mathys, C., and Schlaug, G. (**2008**). "Action-perception mismatch in tone-deafness," Current Biology **18**, R331–332.

Loui, P., Hohmann, A., and Schlaug, G. (**2010**). "Inducing disorders in pitch perception and production: A reverse-engineering approach," Proceedings of Meetings on Acoustics **9**, 1–8.

Mandell, J., Schulze, K., and Schlaug, G. (**2007**). "Congenital amusia: An auditory-motor feedback disorder?," Restorative Neurology and Neurosci. **25**, 323–334.

Meister, I. G., Krings, T., Foltys, H., Boroojerdi, B., Müller, M., Töpper, R., and Thron, A. (**2004**). "Playing piano in the mind—An fMRI study on music imagery and performance in pianists," Brain Res. Cognitive Brain Res. **19**, 219–228

Meyer, M., Alter, K., Friederici, A. D., Lohmann, G., and von Cramon, D. Y. (**2002**). "FMRI reveals brain regions mediating slow prosodic modulations in spoken sentences," Human Brain Mapping **17**, 73–88.

Miller, S. B., and Toca, J. M. (**1979**). "Adapted melodic intonation therapy: A case-study of an experimental language program for an autistic child," J. Clinical Psychiatry **40**, 201–203.

Norton, A., Zipse, L., Marchina, S., and Schlaug, G. (2009). "Melodic intonation therapy: shared insights on how it is done and why it might help," Annals New York Acad. Sci. **1169**, 431–436.

Olsho, L. W., Schoon, C., Sakai, R., Turpin, R., and Sperduto, V. (**1982**). "Auditory frequency discrimination in infancy," Developmental Psychology **18**, 721–726.

Ozdemir, E., Norton, A., and Schlaug, G. (**2006**). "Shared and distinct neural correlates of singing and speaking," NeuroImage **33**, 628–635.

Patel, A. D., Foxton, J. M., and Griffiths, T. D. (**2005**). "Musically tone-deaf individuals have difficulty discriminating intonation contours extracted from speech," Brain Cognition **59**, 310–313.

Patel, A. D., Wong, M., Foxton, J., Lochy, A., and Peretz, I. (**2008**). "Speech intonation perception deficits in musical tone deafness (congenital amusia)," Music Perception **25**, 357–368.

Peretz, I. (**1990**). "Processing of local and global musical information by unilateral brain-damaged patients," Brain **113** (Pt 4), 1185–1205.

Peretz, I. (**2006**). "The nature of music from a biological perspective," Cognition **100**, 1–32.

Peretz, I., Champod, A. S., and Hyde, K. (**2003**). "Varieties of musical disorders. The Montreal battery of evaluation of amusia," Annals New York Acad. Sci. **999**, 58–75.

Pulvermuller, F. (**2005**). "Brain mechanisms linking language and action," Nature Reviews Neurosci. **6**, 576–582.

Rilling, J. K., Glasser, M. F., Preuss, T. M., Ma, X., Zhao, T., Hu, X., and Behrens, T. E. (**2008**). "The evolution of the arcuate fasciculus revealed with comparative DTI," Nature Neurosci. **11**, 426–428.

Schlaug, G., Marchina, S., and Norton, A. (**2008**). "From singing to speaking: why patients with Broca's aphasia can sing and how that may lead to recovery of expressive language functions," Music Perception **25**, 315–323.

Schlaug, G., Marchina, S., Norton, A. (**2009**). "Evidence for plasticity in white-matter tracts of patients with chronic Broca's aphasia underoing intense intonation-based speech therapy," Annals New York Acad. Sci. **1169**, 385–394.

Schlaug, G., Norton, A., Marchina, S., Zipse, L., and Wan, C.Y. (**2010**). "From singing to speaking: Facilitating recovery from nonfluent aphasia," Futures of Neurology (in press).

Schuppert, M., Munte, T. F., Wieringa, B. M., and Altenmuller, E. (**2000**). "Receptive amusia: Evidence for cross-hemispheric neural networks underlying music processing strategies," Brain **123 Pt 3**, 546–559.

Sparks, R., Helm, N., and Albert, M. (**1974**). "Aphasia rehabilitation resulting from melodic intonation therapy," Cortex; a journal devoted to the study of the nervous system and behavior **10**, 303–316.

Sparks, R. W., and Holland, A. L. (**1976**). "Method: Melodic intonation therapy for aphasia," J. Speech Hearing Disorders **41**, 287–297.

Tillmann, B., Janata, P., and Bharucha, J. J. (**2003**). "Activation of the inferior frontal cortex in musical priming," Cognitive Brain Res. **16**, 145–161.

Trainor, L., and Trehub, S. E. (**1994**). "Key membership and implied harmony in Western tonal music: Developmental perspectives," Perception & Psychophysics **56**, 125–132.

Trehub, S. E., Glenn Schellenberg, E., and Nakata, T. (**2008**). "Cross-cultural perspectives on pitch memory," J. Experimental Child Psychology **100**, 40–52.

Trevarthen, C., Aitken, K., Paoudi, D., and Robarts, J. (**1996**). *Children with Autism* (Jessica Kingsley Publishers, London).

Vines, B. W., Nair, D. G., and Schlaug, G. (**2006a**). "Contralateral and ipsilateral motor effects after transcranial direct current stimulation," Neuroreport **17**, 671–674.

Vines, B. W., Schnider, N. M., and Schlaug, G. (**2006b**). "Testing for causality with transcranial direct current stimulation: Pitch memory and the left supramarginal gyrus," Neuroreport **17**, 1047–1050.

Wagner, T., Valero-Cabre, A., and Pascual-Leone, A. (**2007**). "Noninvasive human brain stimulation," Annual Rev. Biomedical Eng. **9**, 527–565.

Wan, C. Y., Demaine, K., Zipse, L., Norton, A., and Schlaug, G. (**2010**). "From music making to speaking: Engaging the mirror neuron system in autism," Brain Research Bulletin. doi:10.1016/j.brainresbull.2010.04.010.

Wan, C.Y., Rüber, T., Hohmann, A., Schlaug, G. (**2010**). "The therapeutic effects of singing in neurological disorders," Music Perception **27**, 287–295.

Wilson, S.J., Parsons, K., Reutens, D.C. (**2006**). "Preserved singing in aphasia: A case study of the efficacy of the Melodic Intonation Therapy," Music Perception **24**, 2336–.

Winkler, I., Haden, G. P., Ladinig, O., Sziller, I., and Honing, H. (**2009**). "Newborn infants detect the beat in music," Proceedings Natl. Acad. Sci. of the USA **106**, 2468–2471.

Zatorre, R. J., and Belin, P. (**2001**). "Spectral and temporal processing in human auditory cortex," Cerebral Cortex **11**, 946–953.

Psyche Loui is an Instructor in Neurology at the Beth Israel Deaconess Medical Center and Harvard Medical School. She received her BS in Psychology and Music from Duke University in 2003, and her Ph.D. in 2007 in Psychology from the University of California at Berkeley. Her main interests include music cognition and auditory perception using the tools of cognitive neuroscience. When not in the lab, she can be seen pondering the acoustics of her violin in various venues in and around Boston.

Gottfried Schlaug is founding director of the Music, Neuroimaging, and Stroke Recovery Laboratories and Chief of Division of Cerebrovascular Diseases at the Department of Neurology, Beth Israel Deaconess Medical Center, and Associate Professor of Neurology at Harvard Medical School. An expert in structural and functional Magnetic Resonance neuroimaging, auditory and motor neuroscience, neuroscience of music, brain plasticity, and stroke recovery, he has (co)-authored over 150 peer-reviewed publications.

Catherine Y. Wan is a Postdoctoral Research Fellow at the Beth Israel Deaconess Medical Center and Harvard Medical School. She received her B.Psych (Hons) in 2000 and M.Psych in 2002 from the University of New South Wales, and her Ph.D. in Psychology from University of Melbourne in Australia in 2009. Her research interests include: music and language development, autism, experience-dependent plasticity as a function of intense skills training, recovery from injury, and blindness as a model to study brain adaptation.

THE BANJO: THE "MODEL" INSTRUMENT

Joseph W. Dickey
3960 Birdsville Rd.
Davidsonville, Maryland 21035

If you stare at a banjo hard enough, you can see two interacting, wave-bearing systems; specifically, strings and a circular membrane. What's more, they are systems for which we can solve the equations of motion and thereby describe the propagation of structural vibrations; i.e., waves. Why this has not been done before is a mystery to me.

At its lowest level of abstraction, the "simplified" banjo shown in Fig. 1 is basically two interacting vibrating systems: a plucked string and a circular membrane. By "interacting" I mean that waves in the string generate waves in the membrane, and visa versa, so that the whole instrument vibrates together. The five-string banjo is a little more complicated as it has six interacting systems—five strings and one membrane. The equations which describe the way waves travel in these systems, how they radiate sound, and how they interact are fairly straightforward. For example, a string has only two coordinates, position and time, and the equation which describes the propagation of a disturbance along the string, the wave equation, links these two variables in such a way that if you know the wave's position at any one time, you know it at any other time. It is an analogous situation in the membrane but complicated somewhat by it being a two dimensional surface and by having the bridge being placed away from the membrane's geometric center.

Another complication, common to both the strings and the membrane, is that every time a wave hits something, it changes as it reflects and/or passes through. With this, the math gets pretty messy.[1] Part of the "art" of modeling is to decide where you can simplify things without throwing out the essence of what you are looking for. For example, there are undoubtedly waves traveling in the neck as though it were a sixth string: are they important? And there are also reverberations within the bridge, tone ring, and other parts: are they important? The model which I developed and describe here does not consider reverberations of waves in these parts, but does account for their influence on the reverberation of waves in the head and strings. As banjo modeling gets more sophisticated, there are many such considerations which will become important, and with this will come more pressure to keep the model as simple a possible while retaining what you set out to discover. In this sense, developing a model is a little like collecting garbage; you really should know what you are going to do with it before you start.

"Developing a model is a little like collecting garbage; you really should know what you are going to do with it before you start."

Why do we go to so much trouble to model the banjo? Partly to build better banjos or help people who fix or play banjos get a better sound by understanding how the various components of the instrument work together to produce the sound. More generally, we do this sort of thing (modeling) to build a better anything. This story describes the why and wherefore of analytical modeling.

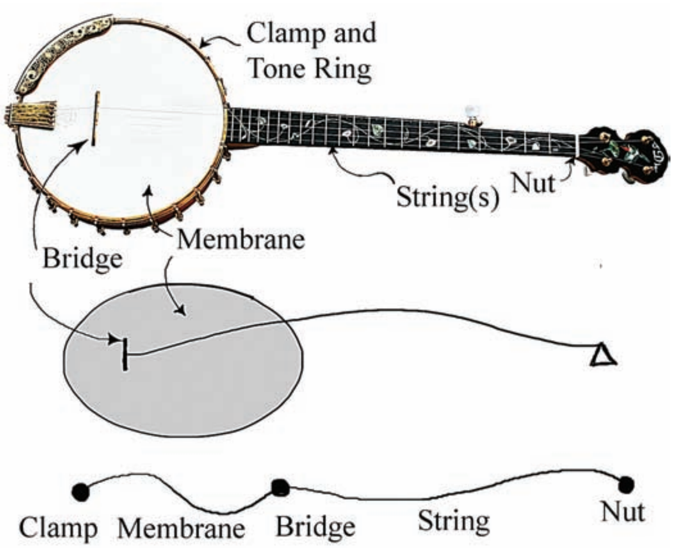


Fig. 1. The banjo simplified. Breaking the banjo down into interacting parts that are individually modeled and solvable.

The strings

Given the tension in the string (provided by the tuning peg) and its mass we know how an initial displacement (a pluck) travels, and given the properties of the nut, bridge and clamp we know how this traveling disturbance reflects off the ends. We call this a structural vibration, or a wave, and this wave will travel back and forth in the string reflecting alternately from one end and the other. And just as it takes some force to contain the end of a jump-rope, it takes force to keep the string connected (through the bridge) to the membrane. We can calculate all of this. Figure 2 describes a pluck in the upper part of the figure as, initially, a triangular shaped displacement shown as a dotted line. The vertical scale in the figure is greatly exaggerated to make it easier to see what is going on. Normally, the displacement of the string is only about one-thousandth of its length. The figure also shows what the string shape would be after about 12 reverberations. Note that the response of the string has diminished in time because there has been energy shared with the other systems and because all the systems have losses. Note, also, that the triangular shape of the pluck has smoothed to the point of looking like our jump-rope; specifically, it resembles the sinusoidal shape we generally expect from a vibrating string. There are several factors which contribute to this smoothing

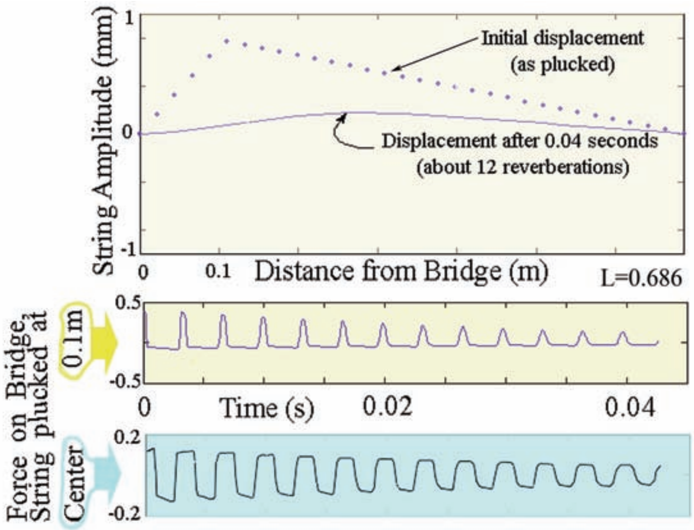


Fig. 2. The calculated amplitude of the string along its length, when plucked, and after about twelve reverberations showing the string "settling in" to a modal shape—a tone.

effect. The largest is that the strings are not completely flexible; they have some stiffness that causes the various frequency components in the wave to travel at different speeds.[2] This disperses or spreads the wave shape as it propagates and is called "dispersion."

Back to the jump-rope analogy. You may recall that it takes some force on your part to hold the end of the rope. For a plucked string, the force analogous to what your hand supplied is supplied by the membrane. I have calculated this force and show it in the lower part of Figure 2. This force, when transferred through the bridge to the membrane, causes the membrane to deflect and radiate sound. The force varies with time, and this variation depends on the shape of the wave hitting the bridge, and this, in turn, is determined by where the string is plucked. Figure 2 shows two illustrative cases: in the top case the string is plucked as shown in the top part of the figure. This is near where a player would normally pluck. In the lower case the string is plucked mid-way between the bridge and the nut. Plucked at the center, the initial shape of the string is a little more like a (half) sine wave than the top curve; and so the imparted force and the shape settle in to a sine-wave shape more quickly, i.e., the string settles into vibrating at a specific frequency that we hear as a particular note. We call this a mode. The settling-in of the pluck to this mode is more apparent in the slow motion, accompanying, movie version of the evolution of the pluck in time. [See sidebar - Movie 1-StringResp] Finally, the settling-in process takes only a small fraction of a second and during that time, the vibration is not modal and, therefore, not a well-defined note. This is the "twang."

The membrane

Like the string, the membrane is also under tension and has mass but in this case waves travel as circles expanding outwardly from their origin rather than along a line. This would be orderly enough except that their origin (the bridge) is not in the center of the circle. As a result, different parts of the expanding wave meet the boundary (the clamp) at different times. It is much easier to visualize this added complexity by looking at the propagation of a very short wave. Such a wave would be impossible to generate experimentally, but in the world of mathematics, we can do pretty much anything. Thus, Fig. 3 shows a snapshot of such a calculated wave which has left the source and traveled to a point where part of the wavefront has reflected from the clamp. Note that the vertical scale is exaggerated and that the pulse goes from positive amplitude (upward) to negative (downward) at the reflection. Every reflection at the clamped edge will cause such a reversal. Also, keep in mind that the wave loses energy (and amplitude) as it travels and when it encounters either the clamp or the bridge. Again, the complexity can be seen more easily in the accompanying time evolution movie [Movie 2-ShortPulse].

The ability to generate such a non-physical pulse and to readily change material properties illustrates several of the major benefits of modeling. In this case it illustrates the com-

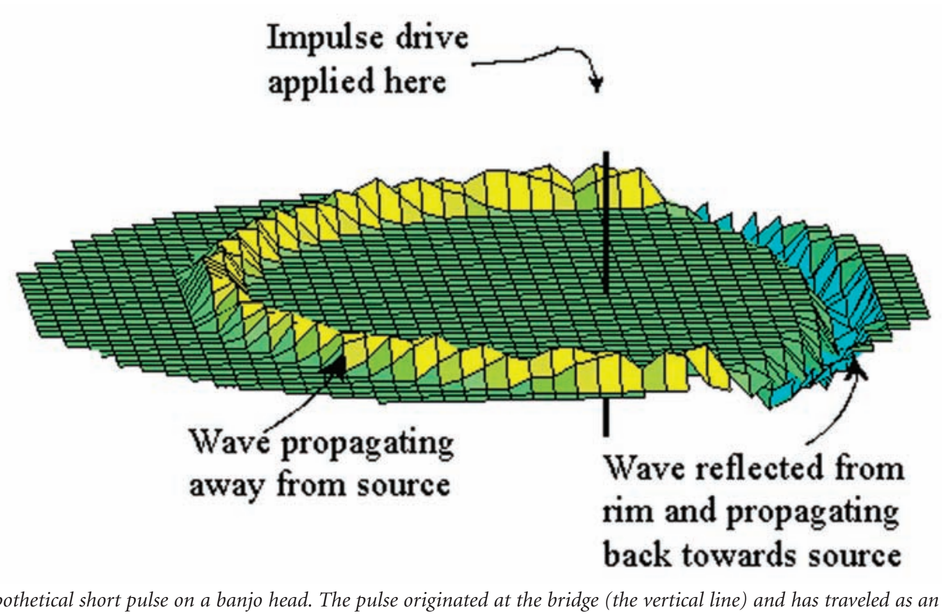


Fig. 3. A "snapshot" of a hypothetical short pulse on a banjo head. The pulse originated at the bridge (the vertical line) and has traveled as an expanding circle, except for that part of the wavefront which has encountered and reflected away from the back edge of the membrane.

plexity of a pulse reverberating in a circular membrane. In other cases, it allows one to play the "what if" game by adjusting parameters with just a few keystrokes. A word of caution here; the "what if" game, while illuminating, can be very irksome to experimentalists who are constrained to real-world materials. Admittedly, the many approximations which go into this and most modeling, mean that analytical models can never be exact. The process is, however, often useful to predict if a proposed change is leading you where you want to go.

Replacing the short pulse with a more realistic excitation imparted to the head by the string, we get head displacements which look quite different and are, in fact, similar to measured results. A snapshot of a calculated head displacement while the head is being driven by a damped sinusoidal oscillation is shown in Fig. 4. Here the frequency of the drive is close to one of the natural resonance frequencies of the head. The accompanying movie of the head response [Movie 3-LongPulse] covers only a fraction of a second in actual time. During this time you can observe the head excitation build for a few tens of milliseconds and then slowly diminish as the drive diminishes and the head dissipates energy. Calculations also allow one to compare the energy lost to material damping and sound radiation.

The head tension

Another advantage of studying the banjo is that many of its set-up parameters are easily adjusted and many of its parts are easily replaced. This is one reason that so many banjo players fiddle with their banjo! One of the most influential parameters is the head tension. Although I do not do much experimental work any more, I do appreciate the need for it and particularly the need for "ground truth" when modeling. So I took my banjo, tapped the head with a screwdriver, and recorded the sound. This "delta function" excitation should, in principle, excite all the head modes and a spectral analysis of the recorded sound should display these modes. The results are shown in Fig. 5.

To calculate the modal response for comparison, I calculated the average magnitude of the head response for harmonic (single frequency) drives as a function of frequency. This would not be exactly the same quantity measured but should show the same frequency peaks. The comparison of measured peaks and calculated ones are shown in Fig. 5.

I could not find tabulated values for the flexural wave speed in mylar membranes under various tensions, so I adjusted the tension in the calculation (a single number in the computer code) until the first peak at 295 Hz matched the measured one; voila, all the other peaks lined up! Also, the

DOWNLOAD THE BANJO VIDEO CLIPS

Shortly after the print copy of this issue is mailed, it will also be published in the Acoustical Society of America's Digital Library. The Table of Contents may be reached directly by going to your internet browser and typing the following Uniform Resource Locator (URL) in the address block: http://scitation.aip.org/dbt/dbt.jsp?KEY=ATCODK&Volume=6&Issue=3. At some point in the download process you will probably be asked for your ID and Password if you are using a computer that is not networked to an institution with a subscription to the ASA Digital Library. These are the same username and password that you use as an ASA member to access the *Journal of the Acoustical Society of America*. Open the abstract for this article by clicking on Abstract. At the bottom of the abstract will be a link. Click on the link and a zipped folder (DickeyData.zip) will be downloaded to your computer (wherever you usually receive downlinks). Unzip the entire folder (as a whole) and open the folder DickeyData. There are 4 files. Do not remove any files—simply open the file called DickeyOpenMe. It is an interactive pdf file. By clicking on any of the hyperlink clips in this file, you should see the video clip associated with that link. The video clip was recorded in QuickTime's .MOV format. If you have difficulty in playing it, you might download the PC or MAC version of *VLC Media Player* from www.videolan.org. This is a non-profit organization that has created a very powerful, cross-platform, free and open source player that works with almost all video and audio formats. Questions? Email the Scitation Help Desk at help@scitation.org or call 1-800-874-6383.

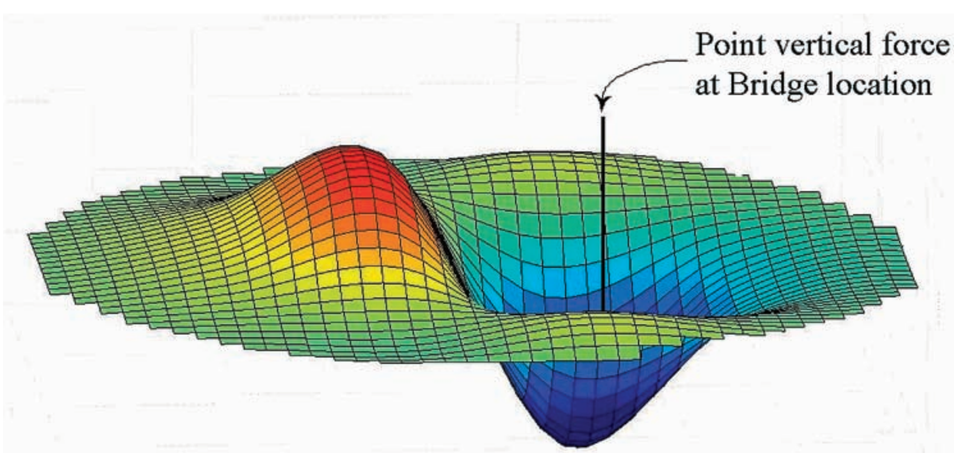


Fig. 4. The highly exaggerated deflection of the head when driven at the bridge position by a damped, sinusoidal force. The frequency of the sinusoid is near a resonance of the head.

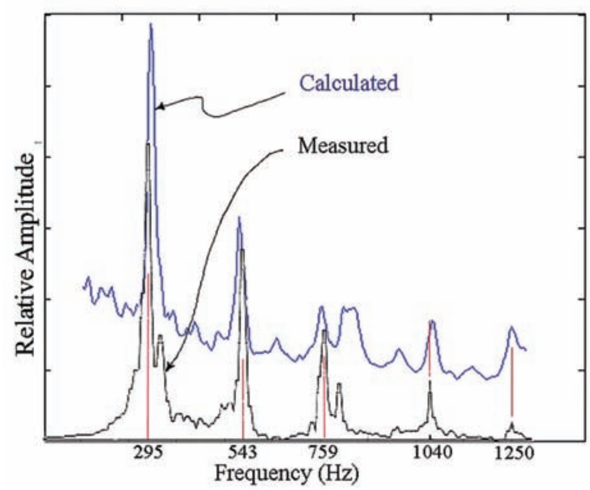


Fig. 5. A comparison of the measured and calculated head frequency response.

speed which did the matching, 150 m/s, is exactly what was used by Rae and Rossing[3] in their measurements of vibration mode patterns of banjo heads.[4]

There are several aspects of Fig. 5 which are of interest. One is that the peaks are not harmonic in the sense that all the higher resonances are multiples of the first harmonic at 295 Hz. Also, the double peak near the third resonance is in both the measured and calculated spectra. I do not know what is causing this. Lastly, there is an exponential "background" in the calculated data which adds a sort of floor to the data and I do not know where that comes from either. If this were subtracted from the response the agreement between experiment and calculation would be remarkable.

The sound

A significant, and certainly the most pertinent energy loss to the membrane waves is the energy radiated as sound. As a section of the membrane moves up, it pushes and condenses the air above it causing a slight increase in ambient pressure; as it subsequently moves down, it forms a rarefaction, a slight decrease from ambient pressure. This alternating pressure/rarefaction is, by definition, a sound wave. The perceived loudness of this sound wave, or the signal recorded by a microphone at some distance from the banjo, is proportional to the average response of the membrane surface.

Here is the procedure for calculating the radiated sound from a plucked banjo:

1) calculate the force (as a function of time) exerted on the banjo head by the plucked string,
2) use this force to excite waves in the head,
3) for each time interval, average (integrate) the response over the surface of the head,
4) plot this as a function of time.

This brings us to Fig. 6 which uses the above prescription with the 1st string plucked at 0.1 m from the bridge. This is the bottom string in the banjo pictured in Fig. 1 and is tuned to 293 Hz. (sometimes referred to as D_4). The tension in the calculation was adjusted so that the first head resonance agreed with the measured one at 295 Hz.[5]

There are several interesting aspects of Fig. 6. First, note that radiated sound increases for the first 30 to 40 ms while energy is being transferred from the string to the membrane. Also note that there are two distinct decay curves: one lasting about 200 ms and the other still persisting at 1 s. It is also interesting that the waveform is much "cleaner" (i.e., sinusoidal) after the instrument settles into the slow decay mode. It is conjecture on my part, but I suspect that the "ragged" waveform in the early stages of sound radiation accounts for the "twang" associated with the classic banjo sound, and the nearly tonal waveform later is the ringing.

So there you have it, summarized in a sentence: a string held at both ends is plucked, it interacts with and causes waves in a membrane which radiates sound. It may seem like a lot of trouble for something which can be summarized in one sentence, but here is the deal. Once the model is on the computer, it takes only a few seconds to calculate allowing you to easily change things like head tension, string gauge, bridge mass, etc. to see what happens to the sound.

And now the bad news. Real world systems are generally too complicated to be modeled accurately. There are a number of "simplifying assumptions" in this and virtually all analytical models. Also, in the case of musical instruments, analytical models compete with the most sophisticated acoustic analyzer of all—the ear. Models and experiments are a long way from discerning the subtleties of "good tone." The evolution of good tone in musical instruments has been largely trial and error

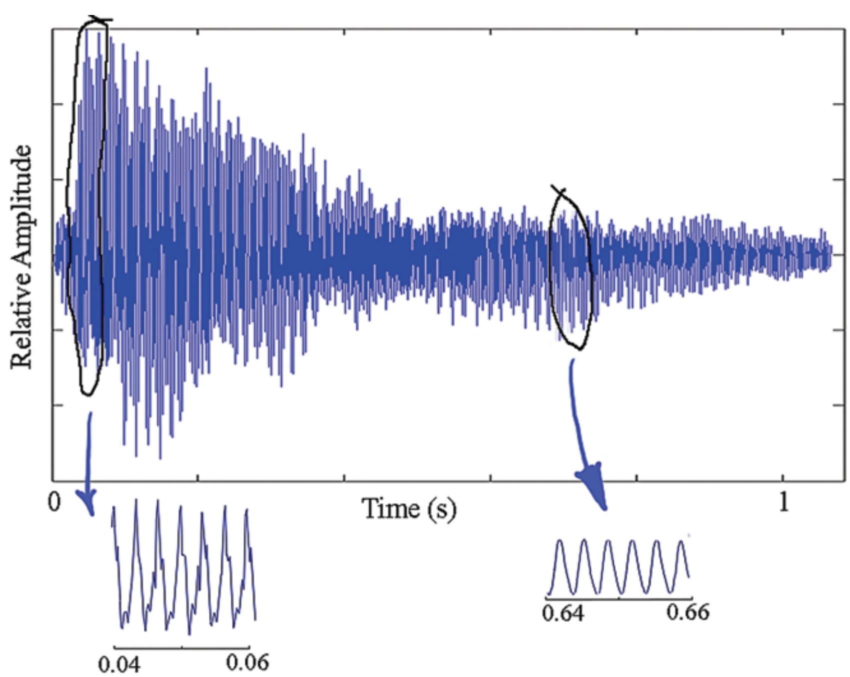


Fig. 6. The calculated sound radiation from the banjo. The detail excerpts show the evolution of the sound from a waveform with significant harmonic content to a nearly sinusoidal shape; i.e., from "twang" to "ring."

and, as such, has been a slow process. Analytical modeling offers a useful tool to estimate the sensitivity of tonal parameters to proposed design changes and possibly shorten the design cycle. There is "sound at the end of the tunnel."**AT**

References

1 J. W. Dickey, "The structural dynamics of the American five-string banjo," J. Acoust. Soc. Am. **114**, 2958–2966 (2003).

2 J. C. Bryner, "Stiff-string theory: Richard Feynman on piano tuning," Physics Today **62**, 46–49 (December 2009). This is a cute article describing a letter from Richard Feynman to his piano tuner in which he expounds on the stiffness of strings and their influence on tuning. See also: N. H. Fletcher and T. D. Rossing, *The Physics of Musical Instruments*, 2nd Edition (Springer, New York, 1998), Section 10.4.3.

3 J. Rae and T. D. Rossing, "Design aspects of the five string banjo" J. Acoust. Soc. Am. **117**, 2590(A) (2005).

4 T. R. Moore and L. A. Stephey, "Time-resolved studies of banjo head motion," J. Acoust. Soc. Am. **127**, 1870(A) (2010).

5 It is not considered good practice to have the head resonance this close to a string resonance, as this seems to produce a very loud note—something like the dreaded "wolf tone" sometimes seen in other stringed instruments. Of course, with the banjo, getting rid of this is just a matter of adjusting the head tension with the tensioning nuts seen around the clamp ring in Fig. 1. Presto, you have moved the head resonance to wherever you want it. Do not try this with your cello.

The author with toys.
(Photo: Michael Ciesielski, Baltimore)

My friends laughed at me when I told them that I wanted to go into modeling as a career. Well here I am, only about 35 years out of graduate school and still holding true to my mantra: "If it has no possible use, it must be good science." I did have a career doing useful work helping make submarines quiet for the Navy, and then a decade with Johns Hopkins University doing research. Altogether I have published about a hundred papers, mostly in structural vibrations. About a third of these were co-authored with the late Gideon Madanik. I spent an interesting year in 1983–84 as a Congressional Science Fellow, was chair of the Acoustical Society of America's Membership Committee for almost a decade, and represented the Society and the American Institute of Physics in various international committees. I am now pretty much retired but still writing a few papers, tending an American Chestnut Foundation orchard on our farm in Davidsonville, Maryland, doing and teaching woodturning, and, oh yes, I play banjo in a couple of local bluegrass bands.

Fig. 1. The ASA Jam

THE SOCIETY: IN A JAM, AND LOVING IT

K. Anthony (Tony) Hoover
McKay Conant Hoover, Inc.
5655 Lindero Canyon Road
Westlake Village, California 91362

The Acoustical Society of America meetings feature a popular new social function, the ASA Jam. The Jam offers an opportunity for members and their guests to play music in a friendly and improvisational setting, using provided equipment and instruments that are arranged in advance through the generous efforts of dedicated volunteers. The Jam extends the invitation to participate or simply, attend to all Society members and their guests.

"The Acoustical Society of America meetings feature a popular new social function—the ASA Jam."

The ASA Jam was inspired by noting that most ASA meetings have musical events that are relatively "non-interactive" in nature. These include concerts, demonstrations, and sessions on all aspects of music. Additionally, many members are deeply involved in music-related professions and activities, and many more play musical instruments. However, there are rarely any active-participation musical events.

In anticipation of the ASA Fall 2007 meeting in New Orleans, the birthplace of so many music traditions, styles, genres, and legends, the Technical Committee on Architectural Acoustics (TCAA) appropriately planned for sessions acknowledging this grand musical heritage. The prospect of active participation in a musical event, in the form of a music jam, had been discussed by a few TCAA members for some time. The New Orleans meeting seemed an ideal opportunity for a definitive action. A request was made for an allowance of up to $1,500 during the New Orleans meeting toward a one-night rental of a local music club, sound system equipment, and musical instruments. This request was loosely based on a Technical Initiative model, but without a specific proposal through a technical committee. Befitting the New Orleans traditions, the intended musical styles were a bit different from most of the classical and opera music that had been the typical focus of many TCAA/ASA presentations—it promoted popular improvisational genres of rock, jazz, and blues. This was a new and unique function for the Society—all for a relatively-small financial outlay. It would require careful planning and effort to arrange and promote, while accommodating all possible concerns for member access and safety.

With good fortune, there was solid support from members of the Society who valued the positive benefits of a new social-interaction paradigm for networking, personal bonding, excitement about attending meetings, student and new member outreach, potential for student/experienced-member interaction, refreshment of the image of the Society, and fun. It was noted that the middle word in the name of ASA is Society (Fig. 1).

The first "TCAA Jam" was arranged by David Woolworth and was held at One Eyed Jacks in New Orleans, an established nightclub within walking distance of the meeting hotel, on Monday evening, 27 November 2007. The $1,500 allocation was spent for the nightclub rental, including the sound system and musical instruments. This TCAA Jam, with nearly constant live music, was well attended by ASA members of all ages and from most of the technical committees. Music ranged from rock to jazz to blues. All feedback spoke of great success and enthusiasm for future jams.

At the Paris TCAA meeting (1 July 2008), a formal Technical Initiative was proposed and unanimously passed for the subsequent Miami meeting (November 2008) based on the New Orleans Jam model. However, due to a variety of challenges, the Miami Jam did not materialize.

At the Miami TCAA meeting (11 November 2008), a new Technical Initiative for $1,500 for a TCAA Jam in Portland was discussed and passed.

The second TCAA Jam was arranged by Tom LePage, and was held in Portland at the meeting hotel bar/restaurant on Tuesday evening, 19 May 2009, complete with sound system and musical instruments (most of which were generously provided by Tom). The $1,500 allocation was to be used for rental and transportation of sound equipment and instruments, as well as a guarantee to the bar/restaurant against a minimum of food and drink sales. Because sales significantly exceeded the minimum, funds were only spent for equipment and instruments, roughly in the amount of $750. The Jam was extremely well attended by ASA members coming from a wide range of ages and technical committees. The bar/restaurant was at full capacity, the music was lively and varied with a rotating lineup of players, and enthusiasm for future jams was renewed with vigor.

At the Portland meeting, the TCAA again voted in favor of a Technical Initiative in the amount of $1,500 for a TCAA Jam at the forthcoming San Antonio meeting (October 2009).

For the San Antonio meeting, Pam Harght attempted to arrange for a venue near the ASA meeting hotel with appropriate accessibility and features, based on the guaranteed-minimum model of the Portland hotel. Unfortunately, no satisfactory arrangements could be achieved with any of the nearby clubs. Therefore the third TCAA Jam was held in a meeting room of the hotel on Monday evening, 26 October 2009. A portion of the allocated funds was spent on equipment rental, in the amount of $550, with costs kept low through some generous donations arranged by Pam. The meeting room was available without further costs to the

Society. All reports were of another highly successful Jam, with renewed enthusiasm for future Jams.

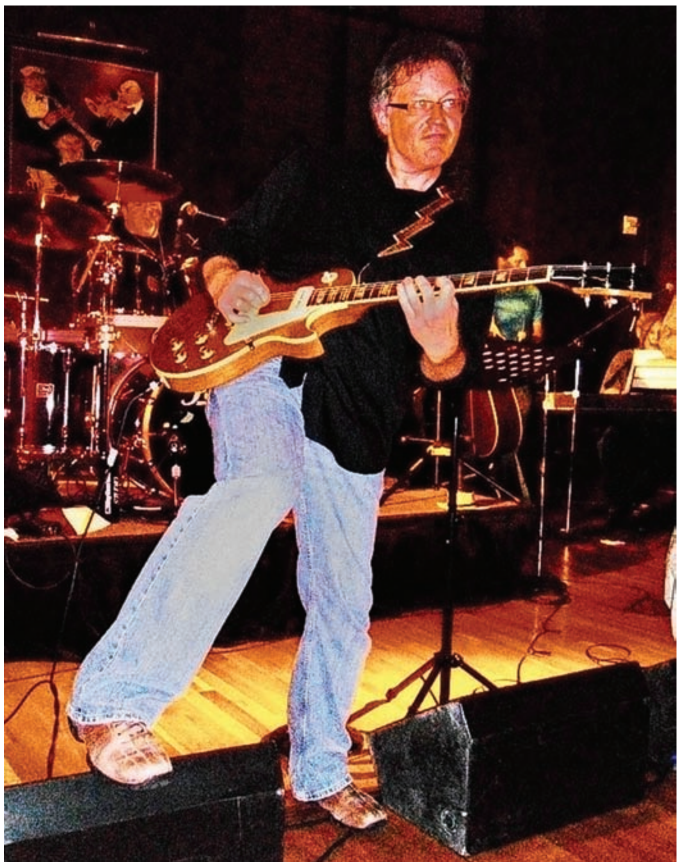
During and subsequent to the Portland ASA meeting, the concept of the Jam was taken up by several parties and committees, including the College of Fellows Steering Committee. Discussions continued through the following year, with ongoing support from the Society. The consensus was that the Jam provided clear value to the Society as a whole, and at a minimal cost.

Subsequently, support and monies were allocated by the Meetings Committee for the next ASA Jam in Baltimore in April 2010. This action relieved the TCAA from requesting Technical Initiative support for the Jam, and underscored that this is an ASA function on behalf of the entire Society.

Kenny Good made all arrangements for the Baltimore meeting. The Jam was held in the hotel lounge, Kozmo's, on Wednesday evening, 21 April 2010. Final costs were $ 762.50, well below the $1,500 allocation—in large part because of another minimum guarantee arrangement with Kozmo's and adroit negotiations with local sound system and instrument rental companies, as well as some donations and contributions arranged by Kenny. Of interest is that the Student Outing for that night was to the Jam. Once again, the Jam was extremely well attended by an enthusiastic crowd.

Thanks to all who have supported and worked so hard to initiate, promote, establish, organize, and participate in these Jams. Special thanks to Dave Woolworth, Tom Lepage, Pam Harght, and Kenny Good for the amount of time, effort, and personal contributions each contributed into making their Jam a success.

We are planning for the next Jam already. It will take place at the Seattle meeting in May 2011. BE THERE! **AT**



Tony Hoover is a principal with McKay Conant Hoover, Inc., and has had the good fortune to consult on over 1,700 architectural acoustics projects and to serve as an expert witness from Federal District Court to US Congressional Hearings. He has a B.A. in American Studies from the University of Notre Dame and an M.S. in Acoustics from the Pennsylvania State University. He has served as President of the National Council of Acoustical Consultants, Chair of the ASA Technical Committee on Architectural Acoustics, and Chair of the ASA College of Fellows. He has held a number of faculty positions such as at the Berklee College of Music and the Boston Architectural Center.

Elaine Moran
Acoustical Society of America
Melville, New York 11747

Leo Beranek

Leo Beranek to receive award from the Institute of Acoustics

Leo Beranek has been named the recipient of the Institute of Acoustics' Peter Barnett Memorial Award. The award will be presented at this year's Reproduced Sound conference in Cardiff in November.

Dr. Beranek, who became an Honorary Fellow of the Institute of Acoustics in 2004, has been cited for the prestigious award in recognition of his "enormous contribution to the field of electro-acoustics, especially in relation to loudspeakers, intelligibility and signal processing."

He received his Doctor of Science from Harvard University, in 1940, and served as Associate Professor of Communications Engineering at Massachusetts Institute of Technology (MIT) from 1947 until 1985, and Technical Director of its Acoustic Laboratory. In 1948 he formed acoustic consulting firm Bolt, Beranek and Newman with MIT colleagues Richard Bolt and Robert Newman (now BBN Technologies).

Leo Beranek has received numerous awards from the Acoustical Society of America including the R. Bruce Lindsay Award (1944), Wallace Clement Sabine Medal (1961), the Gold Medal (1975), and Honorary Fellowship (1994). He has also served in many ASA elected and appointed positions including Vice President (1949) and President (1953).

The Institute of Acoustics is the UK's professional body for those working in acoustics, noise and vibration. It was formed in 1974 and has about 3000 members.

Walter Munk awarded Crafoord Prize

Walter Munk was honored on 11 May by the King of Sweden with the 2010 Crafoord Prize during an award ceremony at the Royal Swedish Academy of Sciences in Stockholm, Sweden. The academy recognized Munk "for his pioneering and fundamental contributions to our understanding of ocean circulation, tides and waves, and their role in the Earth's dynamics." On May 12, Munk gave the 2010 Crafoord Prize Lecture, titled "The Sound of Climate Change" at the Geobiosphere Science Centre at Lund University. His lecture considered how climate change predictions depend on appropriate atmosphere and ocean observations and how underwater transmissions of sound over very long distances—some half way around the globe—can provide evidence of global ocean warming.

In its citation, the academy noted Munk's contributions to several areas of oceanography, but especially to the understanding of circulation and tides. The prize committee also recognized Munk's contributions to other fields such as biology and astronomy that were not even fully appreciated until several decades after he performed his original work.

Winners of the Crafoord Prize receive $500,000. The prize fund was established in 1980 by a donation to the Royal Swedish Academy of Sciences from Anna-Greta and Holger Crafoord. The Crafoord Prize was awarded for the first time in 1982 and recognizes achievement in astronomy and mathematics and biosciences in addition to geosciences. Each discipline is recognized annually in rotating fashion. The prize also periodically recognizes achievement in the field of polyarthritis.

Walter Munk received a Ph.D. in oceanography in 1947 from Scripps Institution of Oceanography and has spent his entire professional career at Scripps. In 1947 he became an

Walter Munk

assistant professor. In 1954 he became a professor of geophysics and also was named a member of the University of California's Institute of Geophysics, and, in 1960, he established a branch of the institute on the Scripps campus in La Jolla, California. Until 1982, he served as director of the Scripps branch and as an associate director of the university-wide institute, which was renamed the Institute of Geophysics and Planetary Physics (IGPP).

Dr. Munk has won numerous awards during his research career. He received the National Medal of Science in 1983 and the 1999 Kyoto Prize in Basic Sciences for his fundamental contributions to the field of oceanography, the first time the prize was awarded to an oceanographer. In 2001, he was the inaugural recipient of the Prince Albert I Medal in the physical sciences of the oceans, which Prince Rainier of Monaco created in cooperation with the International Association for the Physical Sciences of the Oceans. Dr. Munk was named an Honorary Fellow of the Acoustical Society of America in 2004.

The Royal Swedish Academy of Sciences is an independent organization whose overall objective is to promote the sciences and strengthen their influence in society. Every year the Academy awards the Nobel Prizes in Physics and Chemistry, the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel, the Crafoord Prize and a number of other large prizes.

Ronald Aarts awarded AES Silver Medal

Ronald M. Aarts, Professor at Eindhoven University of Technology, was awarded the Audio Engineering Society Silver Medal. The citation read: "With this medal the society recognizes your outstanding contributions to research and applications of signal processing in acoustics and sound reproduction."

Ronald Aarts received a BSc degree in electrical engineering in 1977, and a Ph.D. in physics from Delft University of Technology in 1995. He joined the Optics group at Philips Research Laboratories, Eindhoven, the Netherlands in 1977. In 1984 he joined the Acoustics group at Philips Research Laboratories and worked on the development of CAD tools and signal processing for loudspeaker systems. In 1994 he became a member of the Digital Signal Processing (DSP) group at Philips Research Laboratories and has led research projects on the improvement of sound reproduction, by exploiting DSP and psycho-acoustical phenomena. In 2003 he became a Research Fellow at the Philips Research Laboratories, and extended his interests in engineering to medicine and biology. He has published a large number of papers and reports and holds over 140 first patent application filings including over thirty granted US-patents in the afore mentioned fields. He has served on a number of organizing committees and as chairman for various international conventions. He is a Fellow of the IEEE, a Fellow and past-governor of the AES (Audio Engineering Society), a member of the NAG (Dutch Acoustical Society), the ASA (Acoustical Society of America), the VvBBMT (Dutch Society for Biophysics and Biomedical Engineering), and the NSWO (Dutch Society for Sleep and Wake Research).

ASA President Diemer de Vries (l) and Ronald M. Aarts (r)

The AES's Silver Medal Award was established in 1971 in honor of audio pioneers, such as Alexander Graham Bell and Thomas Edison, and is presented to people who have made an outstanding contribution to the field of audio engineering. The Audio Engineering Society was founded in 1948 and has grown to become an international organization that unites audio engineers, creative artists, scientists and students worldwide by promoting advances in audio and disseminating new knowledge and research. The AES currently has over 14,000 members around the world.

ASU professors receive publication awards

A recent article by Michael Dorman, Professor of Speech and Hearing Science and Tony Spahr, Research Associate of Speech and Hearing Science, at Arizona State University was recently cited in The Hearing Journal Volume 63, June 2010 as one of the "Most Thought Provoking" articles in the area of cochlear implants in 2009. An annual evaluation of research articles is conducted each year by *The Hearing Journal* and for the second time in recent years an article written by Dr. Dorman has been cited. This year's article is: M.F. Dorman, R. Gifford, K. Lewis, S. McKarns, J. Ratigan, A. Spahr, "Word recognition following implantation of conventional and 10-mm hybrid electrodes" in Audiology & Neurotology 14(3), 181-189 (2009). Dr. Dorman is a Fellow of the Acoustical Society of America.

Julie Liss, Associate Professor in the Motor Speech Disorders Laboratory at Arizona State University, and her co-authors have been named the winners of the 2009 *Journal of Speech, Language, and Hearing Research* (JSLHR) Editor's Award for their article, "Quantifying Speech Rhythm Deficits in the Dysarthrias". [Liss, J.M., White, L. Mattys, S.L., Lansford, K., Lotto, A.J., Spitzer, S., and Caviness, J.N., Quantifying speech rhythm deficits in the dysarthrias. Journal of Speech, Language, and Hearing Research, 52(5), 1334- 1352 (2009); Research supported by NIH NIDCD R01 DC006859, J. Liss PI]An article selected for an Editor's Award is the one that the

Michael Dorman

Julie Liss

Vitalyi Gusev

Editor and Associate Editor feel meets the highest quality standards in research design, presentation, and impact for a given year. The award will be presented at the 2010 convention of the American Speech-Language-Hearing Association on 19 November. Dr. Liss is a member of the Acoustical Society of America.

Vitalyi Gusev receives Humboldt Research Award

Vitalyi Gusev, Professor at the Université du Maine, Laboratoire de Physique de l´Etat Condense, has been elected the recipient of a Humboldt Research Award.

The Humboldt Award is conferred in recognition of lifetime achievements in research. In addition, the awardee is invited to carry out research projects of his own choice in cooperation with specialist colleagues in Germany.

Professor Gusev is an international authority in the fields of photo-acoustic phenomena and nonlinear acoustics. He made important theoretical predictions and pioneered the theoretical framework for several photo-acoustic effects. In close collaboration with experimental physicists throughout the world his predictions have been verified and new insight has been gained into acoustic phenomena on picosecond time scales. During his stay in Germany he will focus on the theoretical description of acoustic phenomena in nanostructures and optically excited nanomechanical systems.

ASA Awards Presented at International Science and Engineering Fair ISEF

The Acoustical Society of America (ASA) presented awards to four high school students during the annual Intel International Science and Engineering Fair (Intel ISEF) held this year in San Jose, California. The Intel ISEF, the world's largest international pre-college science competition, annually provides a forum for more than 1,600 high school students from nearly 60 countries, regions, and territories to showcase their independent research. The fair has been held since 1950 to simulate interest in scientific and engineering careers among high school students. Judges presented awards on behalf of 7 government and 69 professional organizations, including ASA. Our society presented a $1000 first place, $500 second place and two non-cash Honorable Mention certificates. Each awardee also receives a free one-year ASA membership and the mentors and schools of the first and second place winners also receive cash prizes.

It is noteworthy that preliminary analysis of submitted projects revealed the indisputable place of acoustics as a fundamental physical science. Acoustics in a direct and an indirect manner was present in projects in Behavioral and Social Sciences, Chemistry, Computer Science, Earth and Planetary Sciences, Electrical and Mechanics Engineering, Engineering Materials, Energy and Transportation, and Physics.

The first prize was awarded to 15-year old Marian Joan Bechtel from Lancaster Catholic High School in Lancaster, Pennsylvania. Her work was categorized in the Earth and Planetary Sciences section. She presented a project titled "Developing a Process for Seismo-Acoustic Imaging Applied to Humanitarian Demining." In a sand test-bed with plastic and metal land simulators for different positions of harmonic sound source and single geophone, she performed a massive set of measurements of a seismo-acoustic field. Then she processed recorded data using the Pearson Correlation technique for amplitudes and received distinctive images of land mine imitators, including a test-bed filled with wet sand, where traditional electromagnetic mine detectors fail. She demonstrated concentration, vigor and the integrity of a mature person, which were necessary due to the huge amount of measurements.

The second prize was awarded to 18-year old David C. Liu from Lynbrook High School, San Jose, CA. His work was included in the Computer Sciences section. He presented a project titled "Continual Adaptation of Acoustic Models for Domain Specific Speech Recognition." Work was performed in close cooperation with the Massachusetts Institute of Technology team which developed a software package, "Web-Accessible Multi-Model Interface (WAMI)," a lightweight speech recognition service

ASA award winners David Liu (l) and Marian Bechtel (c) with Dr. Nick Maltsev, ASA judge.

for Web browsers and cell phones. This package is not 100% perfect, since algorithms are based on phenomenological data, or on particular speech utterances (complete units of speech). David developed and coded an addition to this package, which trains algorithm on the set of the utterances, recognized with high confidence. He improved the error ratio on 13.8% of 32,000 automatically created utterances. There is also a non-acoustic related part of the project, which reveals David's programmer skills. The work is exceptionally good.

ASA also awarded two Honorable Mention prizes, both in the category of Physics and Astronomy. This year one award went to 15-year old Alexander Matthew Atkinson from Oakton High School, Vienna, VA for experiments with a sonic sled. Another Honorable Mention prize went to 17-year old Ellen Marie Price from Jefferson County International Baccalaureate School in Birmingham, AL for comparison of averaged and individual perimeters of human voices..

The judging team included Dr. Robert Showen, founder and chief scientist of ShotSpotter Inc., Dr. Jay Shopping and Dr. Sci. Nick Maltsev, who presented the awards.

The team was pleased that the awards went to a nice mix of young men and women, and that they included representatives of the physics, engineering, computer science, and medical disciplines of ASA interest. We were uniformly impressed by the growing technical education and skills of today's high-school students, and feel—based on the entire assembly of exhibits—that our scientific and engineering future is falling into increasingly capable hands. We found the fair to be technically exhilarating and would recommend that any ASA member asked to judge next year's fair accept the invitation with enthusiasm.

Nick Maltsev, Dr. Sci.

Calendar of Meetings and Congresses

Compiled by the Information Service of the International Commission for Acoustics

2010

18–22 July,	Cairo, Egypt. 17th International Congress on Sound and Vibration (ICSV17) www.icsv17.org
23–27 August	Sydney, Australia. International Congress on Acoustics 2010. www.ica2010sydney.org
23–27 August	Seattle, Washington, USA. 11th International Conference on Music Perception and Cognition
25–26 and 30–31 August	Sydney and Kaloomba, Australia. International Symposium on Music Acoustics (ISMA 2010) http://isma2010.phys.unsw.edu.au
29–31 August	Melbourne, Australia. International Symposium on Room Acoustics (ISRA2010) www.isra2010.org
30–31 August	Auckland, New Zealand. International Symposium on Sustainability in Acoustics (ISSA 2010) http://issa.acoustics.ac.nz
06–10 September	Graz, Austria. 13th International Conference on Digital Audio Effects http://dafx.de
13–14 September	Lerici, Italy. International Conference on Synthetic Aperture Sonar and Synthetic Aperture Radar www.ioa.org.uk/events/event.asp?id=54
15–18 September	Ljubljania, Slovenia. Alps-Adria-Acoustics Association Meeting joint with European Acoustics Association www.fs.uni–lj/sda/euroregio.html
26–30 September	Makuhari, Japan. Interspeech 2010 –ICSLP www.interspeech2010.org
30 September–03 October	Kambasaf, Japan.International Conference on Auditory-Visual Speech Processing www.avsp2010.org
04–08 October	State College, Pennsylvania, USA. Underwater Acoustics and Signal Processing (Short Course). www.outreach.psu.edu/programs/UnderwaterAcoustics
08–10 October	Tokyo, Japan. 40th AES Conference on Spatial Audio www.aes.org/events/40/
11–14 October	San Diego, California. USA. IEEE 2010 Ultrasonics Symposium E-mail: b.potter@vectron.com
13–15 October	Leon, Spain. 41st Spanish Congress of Acoustics and 6th Iberian Acoustics Congress www.sea-acustica.es
14–16 October	Niagara-on-the Lake, Ont., Canada. Acoustics Week in Canada http://caa-aca.ca/E/index.html
18–22 October,	Nagahama, Japan. 10th International Workshop on Railway Noise (IWRN10) www.rtri.or.jp/IWRN10/first.announcement.html
30 October–03 November	November, Kanawaga, Japan. International Conference on Auditory-Visual Speech Processing www.avsp2010.org
02–03 November	Birmingham, UK. Practical Building Acoustics in an Ever Changing World www.ioa.org.uk/events/event.asp?id=67
15–19 November	Cancún, Mexico. 2nd PanAmerican/Iberian Meeting on Acoustics http://asa.aip.org/meetings.html
18–19 November	Brighton, UK, Reproduced Sound 25 www.ioa.org.uk/viewupcomimg.asp

2011

23–27 May	Seattle, Washington, USA. 161st Acoustical Society of America Meeting http://asa.aip.org/meetings.html
22–27 May	Prague, Czech Republic. International Conference on Acoustics, Speech, and Signal Processing (IEEE ICASSP 2011) www.icassp2011.com
13–17 June	Ottawa, Ontario, Canada. 12th International Conference on Hand-Arm Vibration www.hav12.org
27 June–01 July	Aalborg, Denmark. Forum Acusticum 2011 www.fa2011.org
17–21 July	Williamstown, Massachusetts, USA. Mechanics of Hearing 2011 www.mechanicsofhearing.org
24–28 July	Tokyo, Japan. 19th International Symposium on Nonlinear Acoustics (ISNA 19) www.isna19.com
24–28 July	London, UK. 10th International Congress on Noise as a Public Health Problem (ICBEN) www.icben2011.org
27–31 August	Florence, Italy. Interspeech 2011 www.interspeech2011.org
04–07 September	Osaka, Japan. Internoise 2011 www.internoise2011.com
05–08 September	Gdansk, Poland. International Congress on Ultrasonics http://icu2011.ug.edu.pl/index.html
26–28 October	Cáceres, Spain. TECNIACÚSTICA'11 http://sea-acustica.es

2012

20–25 March	Kyoto, Japan. IEEE International Conference on Acoustics, Speech, and Signal Processing www.icssp2012.com
12–15 August	New York, New York, USA. Internoise 2012 www.internoise2012.com.
09–13 September	Portland, Oregon, USA. Interspeech 2012 http://interspeech2012.org

2013

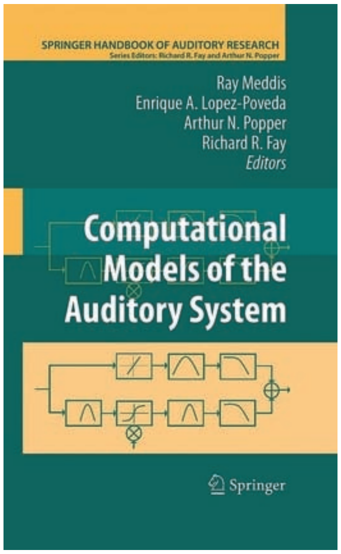
26–31 March	Vancouver, Canada. 2013 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP) www.icassp2013.com
02–07 June	Montréal, Canada. 21st International Congress on Acoustics (ICA 2013) www.ica2013montreal.org

Compiled by Walter G. Mayer, Information Service, ICA.
Please send your meeting announcements to: mayerw@georgetown.edu

Books and Publications

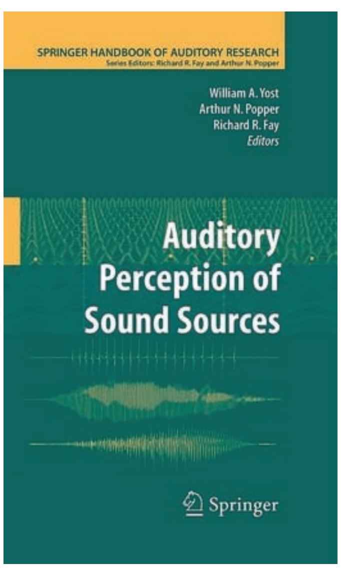
Dick Stern
Applied Research Laboratory, The Pennsylvania State University
PO Box 30, State College, Pennsylvania 16804

Acoustics Today welcomes contributions for "Books and Publications." There is no charge for this service. Submissions of about 250 words that may be edited in MSWord or plain text files should be e-mailed to <acousticstoday@aip.org>. Cover graphics should accompany the text and must be at least 300 dpi. Please send the text and graphics in separate files.



Book Title: *Computational Models of the Auditory System*
Editors: R. Meddis, E. A. Lopez-Poveda, A. N. Popper and R. R. Fay
Publisher: Springer
ISBN: 978-1-4419-1370-8
Pages: 350
Chapters: 7
Binding: Hardcover

Volume 35 in the *Springer Handbook of Auditory Research series, Computational Models of the Auditory*, has at its unifying theme a systems approach where the focus is on studies whose intent is to contribute to the big picture of hearing function. Models have always been a special feature of hearing research. The particular models described in this book are special because they seek to bridge the gap between physiology and psychophysics and ask how the psychology of hearing can be understood in terms of what we already know about the anatomy and physiology of the auditory system. However, although we now have a great deal of detailed information about the outer, middle, and inner ear as well as an abundance of new facts concerning individual components of the auditory brainstem and cortex, models of individual anatomically defined components cannot, in themselves, explain hearing. Instead, it is necessary to model the system as a whole if we are to understand how man and animals extract useful information from the auditory environment. A general theory of hearing that integrates all relevant physiological and psychophysical knowledge is not yet available but it is the goal to which all of the authors of this volume are contributing



Book Title: *Auditory Perception of Sound Sources*
Editors: W. A. Yost, A. N. Popper, A. N., and R. R. Fay
Publisher: Springer
ISBN: 978-0-387-71304-5
Pages: 332
Chapters: 11
Binding: Hardcover

Auditory Perception of Sound Sources, volume 29 in the *Springer Handbook of Auditory Research* series, covers higher-level auditory and perceptual processes. The volume proceeds from the idea that what we hear are not sounds as much as sound sources. The chapters, all written by experts in the field, describe how humans and other animals perceive the entities that are the many sound sources existing in the world. This book provides an overview of areas of current research involved with understanding how sound-source determination and segregation processes operate. This book focuses on psychophysics and perception in humans and animals as well as being relevant to basic auditory research.

Editor's Note—The items printed in "Books and Publications" are reported for informational purposes only and are not necessarily endorsements by the Editor, *Acoustics Today*, or the Acoustical Society of America.

Business Directory

Index to Advertisers

Brüel & Kjær . . . . . Cover 4
www.bksv.com

Campanella Associates 51
www.CampanellaAcoustics.com

Head AcousticsInc. 51
www.headacoustics.com

HGC Engineering 51
www.hgcengineering.com

Maxxon Corporation 4
www.MaxxonCorporation.com

Microflown Technologies . . . . . Cover 2
www.microflown.com

Minus K® Technology . . . . . Cover 3
www.minusk.com

Odeon 23
www.odeon.dk

Scantek, Inc. 3
www.scantekinc.com

Sound Fighter Systems 13
www.soundfighter.com

Western Electro-Acoustic Laboratory 41
www.weal.com

Zero International 25
www.zerointernational.com

Advertising Sales & Production

For advertisement reservations or further information please contact:

Deborah Bott
Advertising Sales Manager
Acoustics Today
c/o AIP Advertising Department
2 Huntington Quadrangle
Suite 1NO1
Melville, NY 11747
Ph: (800) 247-2242
Ph: 516-576-2430
Fax: 516-576-2327
Email: dbott@aip.org

For advertisement production inquiries, please contact and send files to:

Christine DiPasca
Sr. Advertising Production Manager
Acoustics Today
c/o AIP Advertising - Production Operations
2 Huntington Quadrangle
Suite 1NO1
Melville, NY 11747
Ph: 516-576-2434
Fax: 516-576-2638
Email: cdipasca@aip.org

To view a pdf file of the Media Kit visit:
asa.aip.org/ATmediakit.pdf