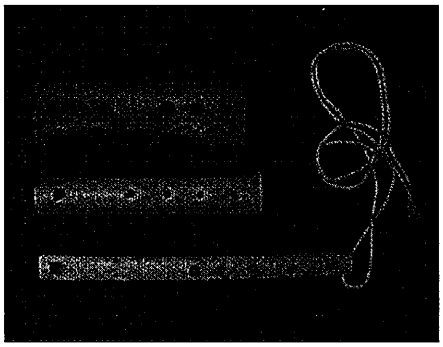
Musical sounds form an exciting, natural conduit between members of our own species, between our species and others, and between the arts and sciences. By looking at musical commonalities, our understanding of music is enlarging, and by viewing musical sounds as an intuitive, nonverbal form of communication, we can better understand our own development in a biodiverse world.



No bones about Neanderthal music. Reconstructions of (**top**) a 53,000-year-old Neanderthal flute made of bear bone found in Slovenia (possibly recorder type), (**middle**) a 30,000-year-old French deer bone flute (most likely recorder type), and (**bottom**) a 4000-year-old French vulture bone flute (definitely recorder type).

It has been postulated that there is an unproven (and probably unprovable) concept called mathematical Platonism, which supposes that there is a universal mathematics awaiting discovery. Is there a universal music awaiting discovery, or is all music just a construct of whatever mind is making it—human, bird, whale? The similarities among human music, bird song, and whale song tempt one to speculate that the Platonic alternative may exist—that there is a universal music awaiting discovery.

It is not known when the ancient art of making music first began. But, if it is as ancient as some believe, this could explain why we find so much meaning and emotion in music even though we cannot explain why it makes us feel the way it does. Such an impenetrable vagueness about this most basic of human creations seems to signal that the roots of music lie closer to our ancient lizard brain than to our more recent reasoning cortex, that music has a more ancient origin even than human language.

References and Notes

1. The BioMusic Program is a program of National Musical Arts (NMA), the resident ensemble of the National Academy of Sciences. The program emerged from NMA's involvement in the National Forum on BioDiversity conference co-hosted by the National Academy of Sciences and the Smithsonian Institution in 1986. It now serves as a think tank for a diverse group of scientists and musicians. The BioMusic Program is a unique conduit between art and science, as it seeks to examine music in all species and to explore and understand its powerful role in all living things. This Perspective summarizes presentations at the BioMusic Symposium held as part of the American Association for the Advancement of Science Annual Meeting (17 to 22 February 2000, Washington, DC). We dedicate this Perspective to our colleague Dr. Luis Baptista (deceased July 2000).
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PERSPECTIVES: BIOLOGY AND MUSIC

Music of the Hemispheres

Mark Jude Tramo

All of us are born with the capacity to apprehend emotion and meaning in music, regardless of whether we understand music theory or read musical notation. Without conscious effort, the human brain is able to translate spectral and temporal patterns of acoustic energy into music's basic perceptual elements: melody, harmony, and rhythm (see the figure, next page). Music, like language, is an acoustically based form of communication with a set of rules for combining a limited number of sounds in an infinite number of ways (*1*). Universal among human cultures, music binds us in a collective identity as members of nations, religions, and other groups.

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It is astonishing how early in life musical competence can be demonstrated (*2*). By 4 months of age, babies prefer consonant musical intervals (major and minor thirds) to dissonant musical intervals (minor seconds) (*3*). Even if an infant's preference for consonant intervals has been influenced by 6 to 7 months of exposure to music in the womb, it is likely that the human brain enters the world primed to extract the spectral and temporal regularities that characterize popular music. Developmental psychologists are joining forces with ethnomusicologists to investigate whether babies weaned on non-Western music also "prefer" consonant intervals like major thirds.

Rats and starlings can distinguish chords deemed consonant and dissonant by Western standards (*3, 4*). Many of the auditory pathways that we use to perceive music evolved in animals for communication, sound source identification, and auditory object segregation. The prevalence of octaves and fifths in music from many different cultures may be a consequence of the way that our ears and brains are built.

"The Star-Spangled Banner" (the American national anthem) illustrates the close relation between the musical chord known as the major triad, a cornerstone of Western harmony, and the harmonic series, "the built-in preordained universal" and "common origin" of all music according to the composer Leonard Bernstein (*5*). We find that the first three notes of any major triad (root position) correspond to the fourth, fifth, and sixth harmonics of any harmonic series (*6*). Residing in the cochlea of our inner ear is the basilar membrane. This membrane behaves like guitar strings of varying thickness, enabling groups of sensory receptors (hair cells) along its length to become activated in response to sounds of specific frequencies (see the figure, page 56). The pattern of hair cell excitation is as orderly as the arrangement of keys on a piano, with equal steps along the chromatic scale mapped out as equal distances along the basilar membrane (*7*). However, different groups of sensory hair cells and their associated neurons are activated by different major triads, even by different inversions of the same triad. So, how is the characteristic harmonic structure of the major triad represented in the brain? In the auditory nerve, which transmits information in the form of action potentials from the inner ear to the brainstem, the neural excitation map may encode the octave the triad is played in; the timing of neural activity may indicate the pitch of each note and the consonance of the combination of

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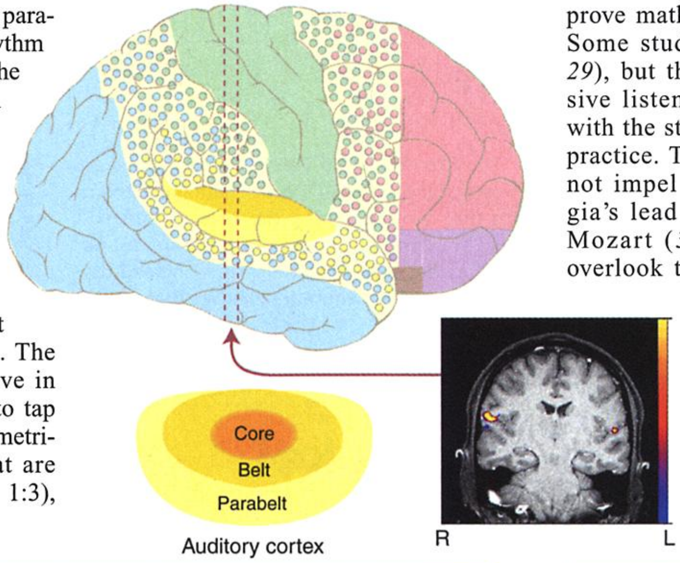
notes (*8*, *9*). Differences in the timing of successive action potentials that are smaller than one-thousandth of a second may determine whether the triad sounds consonant or dissonant.

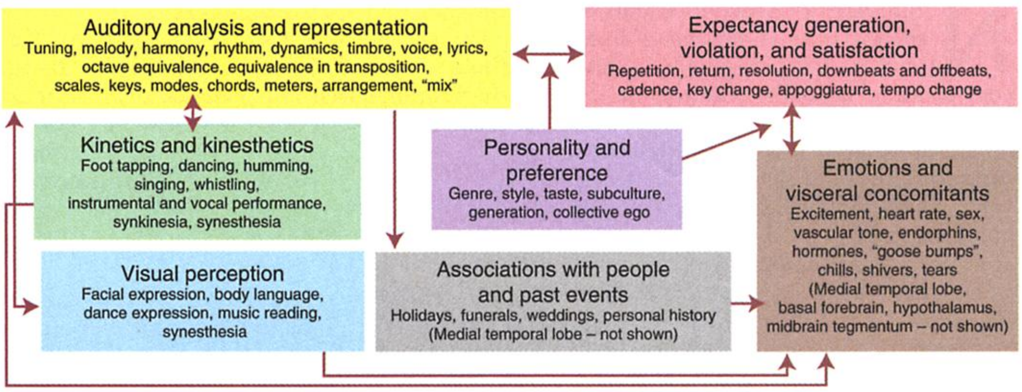
Although the right hemisphere of the human brain has been traditionally viewed as the "musical hemisphere," there is evidence from patients with brain damage and from functional imaging studies that our perception of music emerges from the interplay of neural pathways in both the right and left hemispheres, some specific to music, others not. The right auditory cortex is crucial for perceiving pitch and some aspects of melody, harmony, timbre, and rhythm (see the figure, this page) (*10–16*). Recent evidence from patients with epilepsy suggests that different regions of the auditory cortex (belt and parabelt) process different aspects of rhythm (*16*). The belt and parabelt areas in the right hemisphere discriminate local changes in note duration and separation, whereas grouping by meter involves mostly anterior parabelt areas in both hemispheres. When you tap out a rhythm with your finger, motor areas in the frontal cortex are, of course, active. But, they are also active when you are just listening and preparing to tap (*17*). The particular brain areas that are active in right-handed individuals preparing to tap depends on the type of rhythm: For metrical rhythms, which have beats that are evenly spaced at integer ratios (1:2, 1:3), left frontal cortex, left parietal cortex, and right cerebellum are active; for nonmetrical rhythms (1:2.5), which are harder to tap out, more of the cortex and cerebellum are involved, with a shift in frontal cortex activation to the right hemisphere. Imagine how much of the brain lights up when we dance! How does the brain integrate the barrage of information processed by its auditory, motor, kinesthetic, vestibular, somesthetic, and visual systems?

The areas in the brain where we hear music are partially segregated from those where we feel it. Aesthetically relevant differences in melodic and harmonic progressions are associated with different patterns of cerebral (*18*) and autonomic activity (*19*). If a melody is played correctly on the piano with the right hand, while the left hand plays off-key notes an octave below, infants in the audience would start to squirm (*3*), and most adults, finding it unpleasant, would sustain increased activity in the right medial temporal cortex and left posterior cingulate cortex (*18*). If the left hand had played the correct accompaniment, there would have been no such fuss, and most adults, finding it relatively pleasant, would enjoy increased activity in the right orbitofrontal cortex. Whether the music is pleasant or unpleasant, the auditory cortex, which has connections with these regions (*20*), is working away in both hemispheres. It remains to be seen whether more subtle melodic or rhythmic manipulations that color musical aesthetics (*21*) involve the same brain regions.

There is no "music center" in the brain, no grossly identifiable brain structure that works solely during music cognition. All of the structures that participate in the processing of music contribute to other forms of cognition. For example, the left planum temporale, the pride of musicians with perfect pitch (*22*), is also involved in language processing. However, distinctive patterns of neural activity within the auditory cortex and unique connections between the auditory cortex and other areas of the brain may imbue specificity to the processing of music (*23*).

The brain areas that are active during music perception and performance appear to retain their neural plasticity well into childhood (*22*, *24–27*). This raises the question: Is it possible that boosting brain activity through music could improve math, reading, and spatial skills? Some studies suggest that it can (*28*, *29*), but the short-lived effects of passive listening should not be confused with the stronger effects of training and practice. The available evidence should not impel U.S. states to follow Georgia's lead and baptize newborns with Mozart (*30*), but neither should we overlook the fact that music can positively affect test performance, blood pressure, mood state, pain perception—even oxygen saturation, heart rate, and weight gain in premature infants in intensive care units (*31*). The question of how composers use music to





The anatomy of music. (Top and **bottom)** Areas of the brain that may be involved in different aspects of music perception and performance. **(Inset, left)** Processing of musical sounds takes place in the auditory cortex (yellow), which is located in the superior temporal lobe (*32*). The belt area of the auditory cortex is connected with "lower" processing centers in the core area (dark yellow) and thalamus (not shown), and with "higher" processing centers in the parabelt area (pale yellow) and frontal, parietal, and temporal cortex. (The core area, which includes the primary auditory cortex, is buried within the lateral fissure and cannot be seen on the side view of the brain). The parabelt area is also connected with other cortical areas. These pathways bring music to the parts of the brain that feel, perform, and remember (green, purple, pink, brown, blue). Colored dots indicate areas that perform more than one type of processing. **(Inset, right)** A functional magnetic resonance image showing activation of the core area and adjacent belt area in a normal volunteer, who is listening to Beethoven's Seventh Symphony. The brain activation map was obtained by comparing brain images with the music on or off. Yellow denotes areas of maximal activation; areas with very little or no activation are not colored.

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manipulate emotion is of interest not only to musicians and musicologists, but also to psychologists, movie producers, and, of course, politicians.

Ultimately, if we wish to explore the neurobiological foundations of music, we must design experiments that cross the traditional divide between science and the arts. Understanding music as a universal form of human expression will provide insights into the neurobiology of perception, performance, emotion, learning, development, and plasticity—with a few hints about aesthetics, talent, and creativity thrown in.

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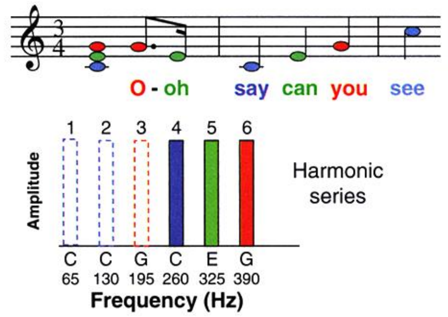
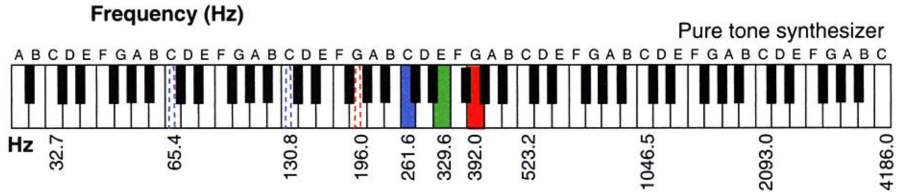
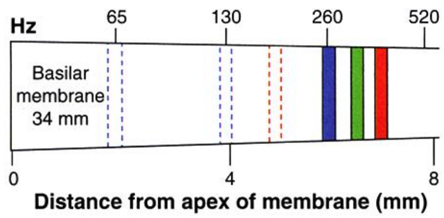
33. I thank P. Cariani, D. Hubel, M. Hauser, M. Gazzaniga, and P. Gray for helpful comments.







"The Star-Spangled Banner." The relation of the first few notes of the U.S. national anthem to the harmonic series, the keys on a piano, and the orderly mapping of different sound frequencies along the basilar membrane of the cochlea. Colors denote frequencies that are an octave apart.

PERSPECTIVES: CHEMISTRY

Switched-On Nickel

Robert H. Crabtree

Nature usually provides chemists with mixtures of substances from which we must separate individual compounds of value. For example, olefins such as ethylene, $H_2C{=}CH_2$, are key intermediates in the petrochemical industry that often need to be separated from refinery mixtures. Sophisticated methods like chromatography can be used for small-scale separation, but industrial-scale work usually requires energy-intensive distillation steps.

Separating compounds by chemical functionality rather than boiling point is a much more attractive concept. For example, olefins can in principle be separated from a mixture by adding a suitable metal or metal complex that selectively forms a complex with the olefin (see structure **1** in the figure). This is a well-known process, but the olefin usually binds reversibly. For the concept to work for separation, the olefin has to bind irreversibly in the absorption step, and there has to be a reliable and practical way to detach the bound olefin from the metal in the release step. In addition, poisoning of the absorbent by common impurities must be avoided; many such impurities tend to bind more tightly to metals than do olefins.

On page 106 of this issue, Wang and Stiefel (*1*) introduce a new approach to the old problem of separation by providing a convenient on/off switch for ligand binding in the form of an electrochemical potential. By adding or removing one electron from a nickel complex, the complex can be switched between several oxidation states. The oxidized state binds the olefin and the reduced states release it (see the figure).

The nickel complex, a dithiolene, has long been known and has always been re-

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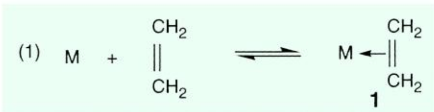

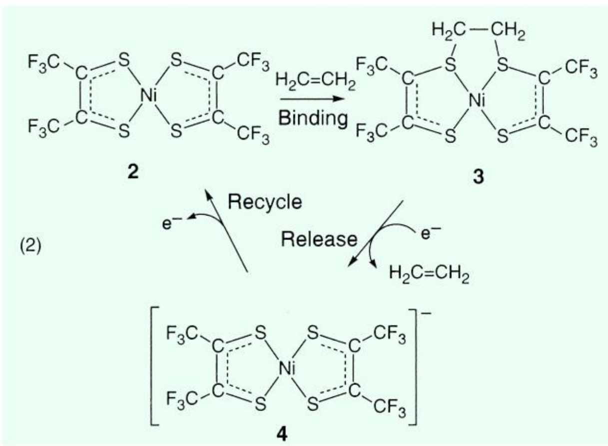

Electrochemical on/off switch. Usually, olefins bind to metal complexes via the metal itself (structure **1**). The nickel complex used by Wang and Stiefel (*1*) is unusual in that when the oxidized complex (structure **2**) encounters an olefin, the olefin binds to the sulfurs (structure **3**). Poisoning by common impurities is thus avoided. The olefin is released through electrochemical reduction of the complex, resulting in structure **4**. It is then ready for another cycle of oxidation, olefin uptake, and reductive release.