

What is the secret of music's strange power? Seeking an answer, scientists are piecing together a picture of what happens in the brains of listeners and musicians

Music and the Brain

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MUSIC SURROUNDS US—AND WE WOULDN'T HAVE IT ANY OTHER WAY.

An exhilarating orchestral crescendo can bring tears to our eyes and send shivers down our spines. Background swells add emotive punch to movies and TV shows. Organists at ballgames bring us together, cheering, to our feet. Parents croon soothingly to infants.

And our fondness has deep roots: we have been making music since the dawn of culture. More than 30,000 years ago early humans were already playing bone flutes, percussive instruments and jaw harps—and all known societies throughout the world have had music. Indeed, our appreciation appears to be innate. Infants as young as two months will turn toward consonant, or pleasant, sounds and away from dissonant ones [see box on page 94]. And when a symphony's denouement gives delicious chills, the same kinds of pleasure centers of the brain light up as they do when eating chocolate, having sex or taking cocaine.

Therein lies an intriguing biological mystery: Why is music—universally beloved and uniquely powerful in its ability

large for grooming, as suggested by Robin M. Dunbar of the University of Liverpool? On the other hand, to use the words of Harvard University's Steven Pinker, is music just "auditory cheesecake"—a happy accident of evolution that happens to tickle the brain's fancy?

Neuroscientists don't yet have the ultimate answers. But in recent years we have begun to gain a firmer understanding of where and how music is processed in the brain, which should lay a foundation for answering evolutionary questions. Collectively, studies of patients with brain injuries and imaging of healthy individuals have unexpectedly uncovered no specialized brain "center" for music. Rather music engages many areas distributed throughout the brain, including those that are normally involved in other kinds of cognition. The active areas vary with the person's individual experiences and musical training. The ear has the fewest sensory cells of any sensory organ—3,500 inner hair cells occupy the ear versus 100 million photoreceptors in the eye. Yet our mental response to

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to wring emotions—so pervasive and important to us? Could its emergence have enhanced human survival somehow, such as by aiding courtship, as Geoffrey F. Miller of the University of New Mexico has proposed? Or did it originally help us by promoting social cohesion in groups that had grown too

music is remarkably adaptable; even a little study can "retune" the way the brain handles musical inputs.

Inner Songs

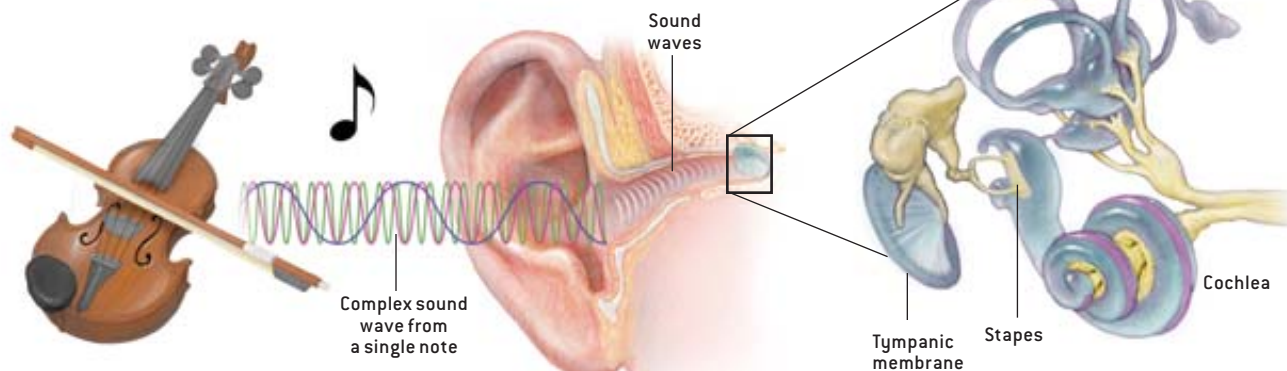
UNTIL THE ADVENT of modern imaging techniques, scientists gleaned insights about the brain's inner musical workings mainly by studying patients—including famous composers—who had experienced brain deficits as a result of injury, stroke or other ailments. For example, in 1933 French composer Maurice Ravel began to exhibit symptoms of what might have been focal cerebral degeneration, a disorder in which discrete areas of brain tissue atrophy. His conceptual abilities remained intact—he could still hear and remember his old compositions and play scales. But he could not write music. Speaking of his proposed opera *Jeanne d'Arc*, Ravel confided to a friend, "...this opera is here, in my head. I hear it, but I will never write it. It's over. I can no longer write my music." Ravel died four years later, following an unsuccessful neurosurgical procedure. The case lent credence to the idea that the brain might not have a specific center for music.

Overview/*The Musical Brain*

- Music has been ubiquitous in human societies throughout the world since the dawn of culture. Appreciation for music appears to be innate; infants as young as two months will turn toward pleasant sounds.
- Many different regions of the brain respond to the perceptual and emotional aspects of music, and the brain alters itself to react more strongly to musical sounds that become important to an individual.
- Scientists who study how music is processed in the brain are laying the groundwork to understand the underlying reasons for music's power and importance to humans.

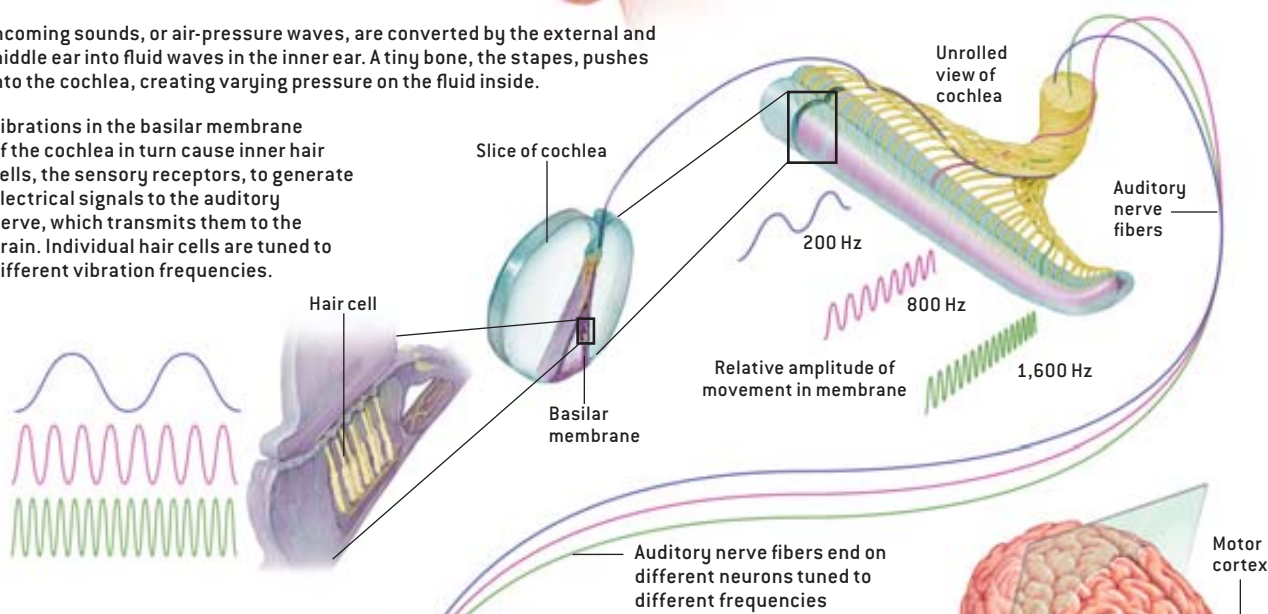
SINGING IN THE BRAIN

When a person listens to music, the brain's response involves a number of regions outside the auditory cortex, including areas normally involved in other kinds of thinking. A person's visual, tactile and emotional experiences all affect where the brain processes music.

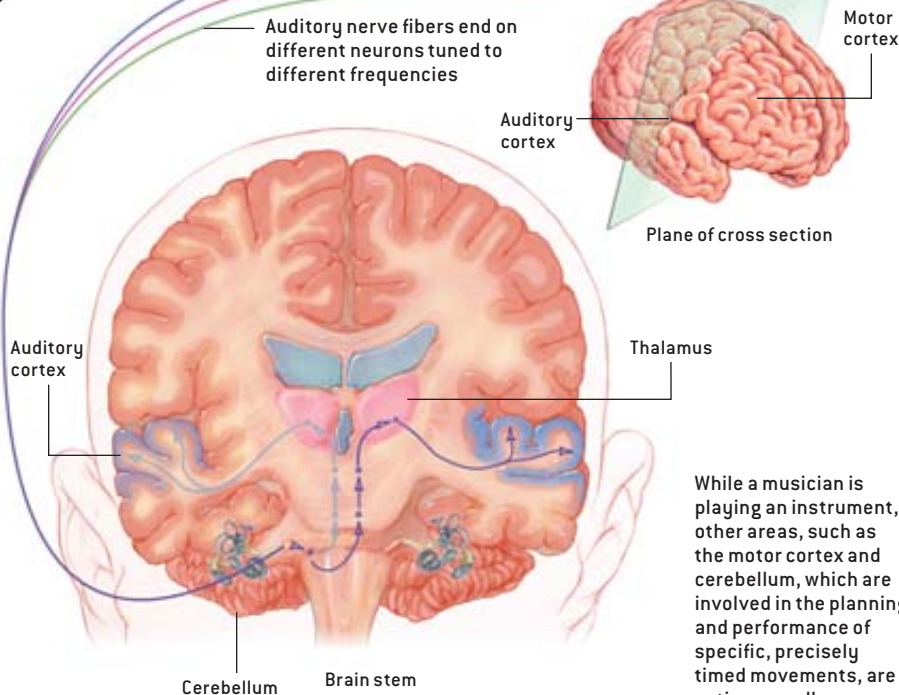


Incoming sounds, or air-pressure waves, are converted by the external and middle ear into fluid waves in the inner ear. A tiny bone, the stapes, pushes into the cochlea, creating varying pressure on the fluid inside.

Vibrations in the basilar membrane of the cochlea in turn cause inner hair cells, the sensory receptors, to generate electrical signals to the auditory nerve, which transmits them to the brain. Individual hair cells are tuned to different vibration frequencies.



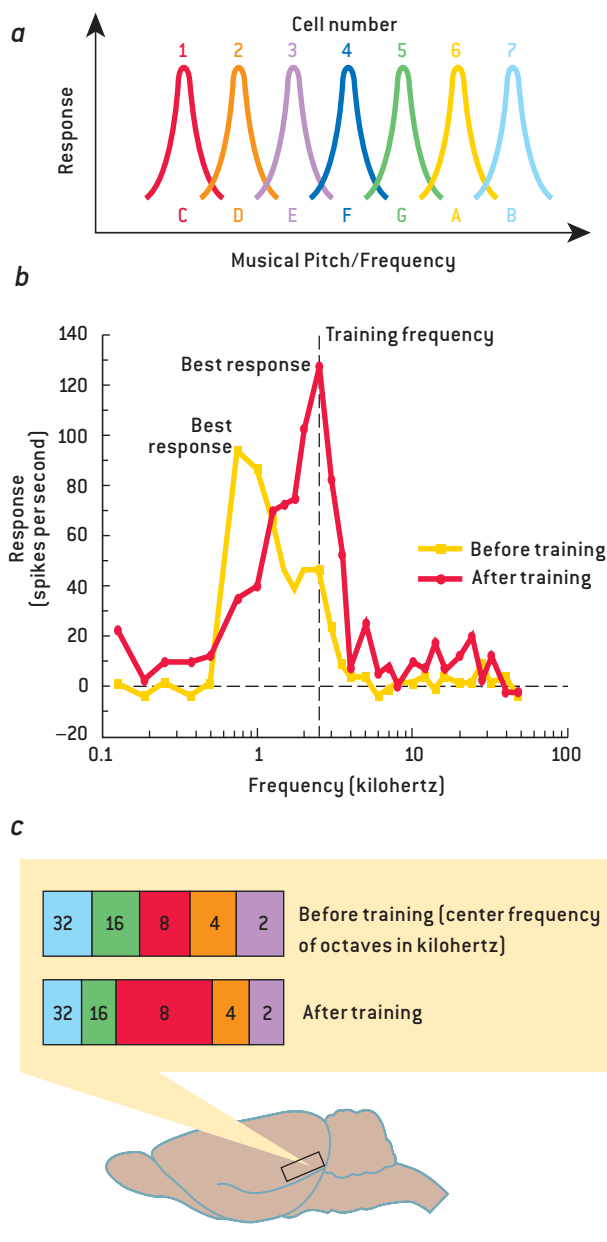
The brain processes music both hierarchically and in a distributed manner. Within the overall auditory cortex, the primary auditory cortex, which receives inputs from the ear and lower auditory system via the thalamus, is involved in early stages of music perception, such as pitch (a tone's frequency) and contour (the pattern of changes in pitch), which is the basis for melody. The primary auditory cortex is "retuned" by experience so that more cells become maximally responsive to important sounds and musical tones. This learning-induced retuning affects further cortical processing in areas such as secondary auditory cortical fields and related so-called auditory association regions, which are thought to process more complex music patterns of harmony, melody and rhythm.



While a musician is playing an instrument, other areas, such as the motor cortex and cerebellum, which are involved in the planning and performance of specific, precisely timed movements, are active as well.

RETUNING THE BRAIN

Individual brain cells each respond optimally to a particular pitch or frequency (a). Cells shift their original tuning when an animal learns that a specific tone is important (b). This cellular adjustment “edits” the “frequency map” of a rat’s brain so that a greater area of the cortex processes an important tone—for instance, it expands the map for eight kilohertz when that is the important frequency (c).



The experience of another composer additionally suggested that music and speech were processed independently. After suffering a stroke in 1953, Vissarion Shebalin, a Russian composer, could no longer talk or understand speech, yet he retained the ability to write music until his death 10 years later. Thus, the supposition of independent processing appears to be true, although more recent work has yielded a

more nuanced understanding, relating to two of the features that music and language share: both are a means of communication, and each has a syntax, a set of rules that govern the proper combination of elements (notes and words, respectively). According to Aniruddh D. Patel of the Neurosciences Institute in San Diego, imaging findings suggest that a region in the frontal lobe enables proper construction of the syntax of both music and language, whereas other parts of the brain handle related aspects of language and music processing.

Imaging studies have also given us a fairly fine-grained picture of the brain’s responses to music. These results make the most sense when placed in the context of how the ear conveys sounds in general to the brain [see box on preceding page]. Like other sensory systems, the one for hearing is arranged hierarchically, consisting of a string of neural processing stations from the ear to the highest level, the auditory cortex. The processing of sounds, such as musical tones, begins with the inner ear (cochlea), which sorts complex sounds produced by, say, a violin, into their constituent elementary frequencies. The cochlea then transmits this information along separately tuned fibers of the auditory nerve as trains of neural discharges. Eventually these trains reach the auditory cortex in the temporal lobe. Different cells in the auditory system of the brain respond best to certain frequencies; neighboring cells have overlapping tuning curves so that there are no gaps. Indeed, because neighboring cells are tuned to similar frequencies, the auditory cortex forms a “frequency map” across its surface [see box at left].

The response to music per se, though, is more complicated. Music consists of a sequence of tones, and perception of it depends on grasping the relationships between sounds. Many areas of the brain are involved in processing the various components of music. Consider tone, which encompasses both the frequencies and loudness of a sound. At one time, investigators suspected that cells tuned to a specific frequency always responded the same way when that frequency was detected.

But in the late 1980s Thomas M. McKenna and I, working in my laboratory at the University of California at Irvine, raised doubts about that notion when we studied contour, which is the pattern of rising and falling pitches that is the basis for all melodies. We constructed melodies consisting of different contours using the same five tones and then recorded the responses of single neurons in the auditory cortices of cats. We found that cell responses (the number of discharges) varied with the contour. Responses depended on the location of a given tone within a melody; cells may fire more vigorously when that tone is preceded by other tones rather than when it is the first. Moreover, cells react differently to the same tone when it is part of an ascending contour (low to high tones) than when it is part of a descending or more complex one. These findings show that the pattern of a melody matters: processing in the auditory system is not like the simple relaying of sound in a telephone or stereo system.

Although most research has focused on melody, rhythm (the relative lengths and spacing of notes), harmony (the relation of two or more simultaneous tones) and timbre (the char-

acteristic difference in sound between two instruments playing the same tone) are also of interest. Studies of rhythm have concluded that one hemisphere is more involved, although they disagree on which hemisphere. The problem is that different tasks and even different rhythmic stimuli can demand different processing capacities. For example, the left temporal lobe seems to process briefer stimuli than the right temporal lobe and so would be more involved when the listener is trying to discern rhythm while hearing briefer musical sounds.

The situation is clearer for harmony. Imaging studies of the cerebral cortex find greater activation in the auditory regions of the right temporal lobe when subjects are focusing on aspects of harmony. Timbre also has been “assigned” a right temporal lobe preference. Patients whose temporal lobe has been removed (such as to eliminate seizures) show deficits in discriminating timbre if tissue from the right, but not the left, hemisphere is excised. In addition, the right temporal lobe

over time without additional training and lasted for months. These findings initiated a growing body of research indicating that one way the brain stores the learned importance of a stimulus is by devoting more brain cells to the processing of that stimulus. Although it is not possible to record from single neurons in humans during learning, brain-imaging studies can detect changes in the average magnitude of responses of thousands of cells in various parts of the cortex. In 1998 Ray Dolan and his colleagues at University College London trained human subjects in a similar type of task by teaching them that a particular tone was significant. The group found that learning produces the same type of tuning shifts seen in animals. The long-term effects of learning by retuning may help explain why we can quickly recognize a familiar melody in a noisy room and also why people suffering memory loss from neurodegenerative diseases such as Alzheimer’s can still recall music that they learned in the past.

Learning retunes the brain, so that more cells respond best to behaviorally important sounds.

becomes active in normal subjects when they discriminate between different timbres.

Brain responses also depend on the experiences and training of the listener. Even a little training can quickly alter the brain’s reactions. For instance, until about 10 years ago, scientists believed that tuning was “fixed” for each cell in the auditory cortex. Our studies on contour, however, made us suspect that cell tuning might be altered during learning so that certain cells become extra sensitive to sounds that attract attention and are stored in memory.

To find out, Jon S. Bakin, Jean-Marc Edeline and I conducted a series of experiments during the 1990s in which we asked whether the basic organization of the auditory cortex changes when a subject learns that a certain tone is somehow important. Our group first presented guinea pigs with many different tones and recorded the responses of various cells in the auditory cortex to determine which tones produced the greatest responses. Next, we taught the subjects that a specific, nonpreferred tone was important by making it a signal for a mild foot shock. The guinea pigs learned this association within a few minutes. We then determined the cells’ responses again, immediately after the training and at various times up to two months later. The neurons’ tuning preferences had shifted from their original frequencies to that of the signal tone. Thus, learning retunes the brain so that more cells respond best to behaviorally important sounds. This cellular adjustment process extends across the cortex, “editing” the frequency map so that a greater area of the cortex processes important tones. One can tell which frequencies are important to an animal simply by determining the frequency organization of its auditory cortex [see box on opposite page].

The retuning was remarkably durable: it became stronger

Even when incoming sound is absent, we all can “listen” by recalling a piece of music. Think of any piece you know and “play” it in your head. Where in the brain is this music playing? In 1999 Andrea R. Halpern of Bucknell University and Robert J. Zatorre of the Montreal Neurological Institute at McGill University conducted a study in which they scanned the brains of nonmusicians who either listened to music or imagined hearing the same piece of music. Many of the same areas in the temporal lobes that were involved in listening to the melodies were also activated when those melodies were merely imagined.

Well-Developed Brains

STUDIES OF MUSICIANS have extended many of the findings noted above, dramatically confirming the brain’s ability to revise its wiring in support of musical activities. Just as some training increases the number of cells that respond to a sound when it becomes important, prolonged learning produces more marked responses and physical changes in the brain. Musicians, who usually practice many hours a day for years, show such effects—their responses to music differ from those of nonmusicians; they also exhibit hyperdevelopment of certain areas in their brains.

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Born to Rock?

Although many people think they are musically impaired, we are all musical to some degree. In fact, to find someone with a “musical brain,” we need only look at any infant. Even before babies have acquired language, they exhibit a marked capacity for reacting to music. Perhaps that is why parents and others instinctively communicate with infants in a musical manner, using wide ranges of pitch and melodiclike phrases, often called “motherese.” All cultures use motherese.

Beyond reacting positively to such communication, infants appear to encourage the performance of their mothers. In a 1999 study by Laura-Lee Balkwill and William F. Thompson, then both at York University in Toronto, North American and East Indian mothers sang the same song both with their infant present and absent. Others later were able to judge accurately in which of the two recordings the infant was present. The study showed as well that at least some musical cues appear to play across cultures. Listeners to the recordings



MUSICAL COMMUNICATION, or “motherese,” is common in all cultures.

could tell if the infant had been present or not regardless of whether they heard the song in their own language or in another.

How do we know infants are aware of music when they can't yet talk? We use objective measures of their behavior. For example, an infant sits on his mother's lap. To the left and right are two loudspeakers and adjacent transparent plastic boxes. Each box is ordinarily dark, but when the tot turns his head toward one it rewards him by lighting up and activating an animated toy, such as a dog or monkey. During testing, a researcher manipulates puppets or other objects directly in front of the baby to

attract attention. A musical stimulus (which can be a single tone or a melody) plays repeatedly from one loudspeaker. At random times, the experimenter pushes a hidden button that changes the stimulus. If the infant notices the difference and turns toward the speaker, he is rewarded with the sight of the toy.

Such tests have revealed that infants differentiate between two adjacent musical tones as well as adults. Babies also notice changes in both tempo, the speed at which music is played, and rhythm. And they recognize a melody when it is played in a different key. Underscoring such studies, Sandra Trehub of the University of Toronto recently found that babies as young as two to six months prefer consonant sounds to dissonant ones. Music learning appears to begin even earlier, however—in utero. Peter Hepper of Queen's University in Belfast found that about two weeks before birth, fetuses recognized the difference between the theme music of the “Neighbors” TV show, heard daily by their mothers for weeks, and a novel song. —N.M.W.

Christo Pantev, then at the University of Münster in Germany, led one such study in 1998. He found that when musicians listen to a piano playing, about 25 percent more of their left-hemisphere auditory regions respond than do so in nonmusicians. This effect is specific to musical tones and does not occur with similar but nonmusical sounds. Moreover, the authors found that this expansion of response area is greater the younger the age at which lessons began. Studies of children suggest that early musical experience may facilitate development. In 2004 Antoine Shahin, Larry E. Roberts and Laurel J. Trainor of McMaster University in Ontario recorded brain responses to piano, violin and pure tones in four- and five-year-old children. Youngsters who had received greater exposure to music in their homes showed enhanced brain auditory activity, comparable to that of unexposed kids about three years older.

Musicians may display greater responses to sounds, in part because their auditory cortex is more extensive. Peter Schneider and his co-workers at the University of Heidelberg in Germany reported in 2002 that the volume of this cortex in musicians was 130 percent larger. The percentages of volume increase were linked to levels of musical training, suggesting that learning music proportionally increases the number of neurons that process it.

In addition, musicians' brains devote more area toward motor control of the fingers used to play an instrument. In 1995

Thomas Elbert of the University of Konstanz in Germany and his colleagues reported that the brain regions that receive sensory inputs from the second to fifth (index to pinkie) fingers of the left hand were significantly larger in violinists; these are precisely the fingers used to make rapid and complex movements in violin playing. In contrast, they observed no enlargement of the areas of the cortex that handle inputs from the right hand, which controls the bow and requires no special finger movements. Nonmusicians do not exhibit these differences. Further, Pantev, now at the Rotman Research Institute at the University of Toronto, reported in 2001 that the brains of professional trumpet players react in such an intensified manner only to the sound of a trumpet—not, for example, to that of a violin.

Musicians also must develop greater ability to use both hands, particularly for keyboard playing. Thus, one might expect that this increased coordination between the motor regions of the two hemispheres has an anatomical substrate. That seems to be the case. The anterior corpus callosum, which contains the band of fibers that interconnects the two motor areas, is larger in musicians than in nonmusicians. Again, the extent of increase is greater the earlier the music lessons began. Other studies suggest that the actual size of the motor cortex, as well as that of the cerebellum—a region at the back of the brain involved in motor coordination—is greater in musicians.

Ode to Joy—or Sorrow

BEYOND EXAMINING HOW the brain processes the auditory aspects of music, investigators are exploring how it evokes strong emotional reactions. Pioneering work in 1991 by John A. Sloboda of Keele University in England revealed that more than 80 percent of sampled adults reported physical responses to music, including thrills, laughter or tears. In a 1995 study by Jaak Panksepp of Bowling Green State University, 70 percent of several hundred young men and woman polled said that they enjoyed music “because it elicits emotions and feelings.” Underscoring those surveys was the result of a 1997 study by Carol L. Krumhansl of Cornell University. She and her co-workers recorded heart rate, blood pressure, respiration and other physiological measures during the presentation of various pieces that were considered to express happiness, sadness, fear or tension. Each type of music elicited a different but consistent pattern of physiological change across subjects.

Until recently, scientists knew little about the brain mechanisms involved. One clue, though, comes from a woman

known as I. R. (initials are used to maintain privacy), who suffered bilateral damage to her temporal lobes, including auditory cortical regions. Her intelligence and general memory are normal, and she has no language difficulties. Yet she can make no sense of nor recognize any music, whether it is a previously known piece or a new piece that she has heard repeatedly. She cannot distinguish between two melodies no matter how different they are. Nevertheless, she has normal emotional reactions to different types of music; her ability to identify an emotion with a particular musical selection is completely normal! From this case we learn that the temporal lobe is needed to comprehend melody but not to produce an emotional reaction, which is both subcortical and involves aspects of the frontal lobes.

An imaging experiment in 2001 by Anne Blood and Zatorre of McGill sought to better specify the brain regions involved in emotional reactions to music. This study used mild emotional stimuli, those associated with people’s reactions to musical consonance versus dissonance. Consonant musical intervals are generally those for which a simple ratio of frequencies exists between two tones. An example is middle C (about 260 hertz, or Hz) and middle G (about 390 Hz). Their ratio is 2:3, forming a pleasant-sounding “perfect fifth” interval when they are played simultaneously. In contrast, middle C and C sharp (about 277 Hz) have a “complex” ratio of about

8:9 and are considered unpleasant, having a “rough” sound.

What are the underlying brain mechanisms of that experience? PET (positron emission tomography) imaging conducted while subjects listened to consonant or dissonant chords showed that different localized brain regions were involved in the emotional reactions. Consonant chords activated the orbitofrontal area (part of the reward system) of the right hemisphere and also part of an area below the corpus callosum. In contrast, dissonant chords activated the right parahippocampal gyrus. Thus, at least two systems, each dealing with a different type of emotion, are at work when the brain processes emotions related to music. How the different patterns of activity in the auditory system might be specifically linked to these differentially reactive regions of the hemispheres remains to be discovered.

In the same year, Blood and Zatorre added a further clue to how music evokes pleasure. When they scanned the brains of musicians who had chills of euphoria when listening to music, they found that music activated some of the same reward systems that are stimulated by food, sex and addictive drugs.



BONE FLUTE from a site in France dates back at least 32,000 years—evidence that humans have been playing music since the dawn of culture.

Overall, findings to date indicate that music has a biological basis and that the brain has a functional organization for music. It seems fairly clear, even at this early stage of inquiry, that many brain regions participate in specific aspects of music processing, whether supporting perception (such as apprehending a melody) or evoking emotional reactions. Musicians appear to have additional specializations, particularly hyperdevelopment of some brain structures. These effects demonstrate that learning retunes the brain, increasing both the responses of individual cells and the number of cells that react strongly to sounds that become important to an individual. As research on music and the brain continues, we can anticipate a greater understanding not only about music and its reasons for existence but also about how multifaceted it really is. SA

MORE TO EXPLORE

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