PERSPECTIVES: NEUROSCIENCE

Mental Models and Musical Minds

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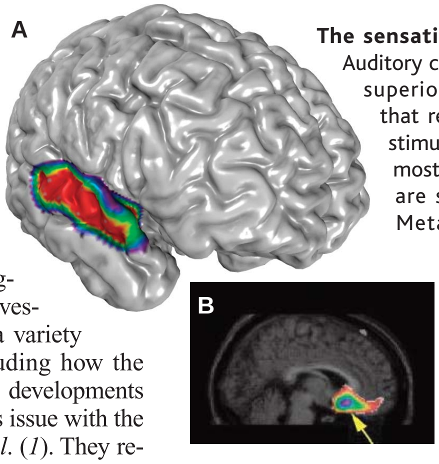


The sensation of music. (A) Auditory cortical areas in the superior temporal gyrus that respond to musical stimuli. Regions that are most strongly activated are shown in red. **(B)** Metabolic activity in the ventromedial region of the frontal lobe increases as a tonal stimulus becomes more consonant.

Music is found in all cultures and has a remarkable diversity of forms. Cognitive scientists have discovered highly specific and detailed knowledge of musical structure even in individuals without extensive musical training. Brain imaging has proved valuable for investigating the neural basis of a variety of cognitive functions, including how the brain processes music. These developments converge on page 2167 of this issue with the research article by Janata *et al.* (*1*). They report that abstract patterns of Western tonal musical structure are mirrored in patterns of brain activity in human subjects.

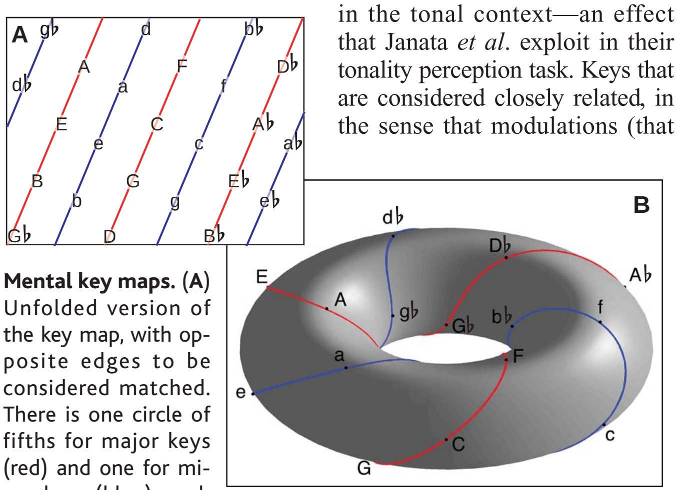
Using functional magnetic resonance imaging, Janata and colleagues analyzed the brain activity of eight musically experienced listeners as they performed two musical perception tasks requiring them to detect a deviance in timbre (a note played by a flute instead of a clarinet) and notes that violated local tonality. The investigators found that the auditory cortex as well as a number of other brain areas were activated in their subjects as they undertook the musical perception tasks. The most consistent activation was along the superior temporal gyrus of both hemispheres. Additional regions that were activated included the temporal, parietal, frontal, and limbic lobes as well as the thalamus and cerebellum, indicating that the processing of music is extremely complicated.

Recent research in neuroanatomy, neurophysiology, and functional brain imaging has investigated the location and properties of auditory cortical fields (*2*). There is an emerging consensus that both the cytoarchitecture and neural connections within auditory cortical fields form the basis of a hierarchy of processing regions in the brain. These regions start in core areas of the primary auditory cortex, and emanate in several processing streams that extend into various portions of the superior and middle temporal gyri (see the top figure). Music offers a way to explore the functional organization of these putative processing streams. Auditory cortical regions have extensive, spatially organized projections to and from frontal and parietal lobes. These extended cortical networks are thought to underlie the complex neural events engaged during the processing of complex sounds. Even a seemingly simple musical task such as perceiving and recognizing a melody entails a variety of cognitive processes, including perceptual, attentional, mnemonic, and affective responses.

Music seems to depend on specific brain circuitry, because it can be dissociated from processing of other classes of sounds, including speech, in individuals with certain diseases or brain lesions. This concept is supported by functional imaging studies, which reveal that there are specialized activity patterns for tonal processing, including those found in the temporal and frontal brain areas that are critical for tonal working memory. In addition, as Janata and colleagues confirm, there are hemispheric asymmetries; for example, the right side of the brain is preferentially activated during the processing of musical pitch (*3*). Initial studies on the affective response to music implicate a variety of neural structures in limbic and paralimbic brain areas, as well as in midbrain and basal forebrain regions linked to reward and motivation (*4*). One area consistently modulated by affective responses is the ventromedial frontal cortex (see the top figure), the principal region identified by Janata *et al.* as showing sensitivity to tonality.

A separate line of investigation originates with research into the psychological reality of theoretical descriptions of music. Are listeners and performers influenced by the tonal, harmonic, melodic, rhythmic, and metric patterns identified in music theory? If so, does this knowledge influence how a listener organizes and remembers music, and how a musician plans and executes a performance? Empirical studies have extensively documented the precise contents of this knowledge and show that it largely conforms to descriptions of music theory. Many aspects of music, such as whether notes are played in tune, appear to be acquired implicitly—that is, without explicit formal instruction—and the influence of this knowledge is manifest in a wide range of musical behaviors.

One of the most developed areas in the cognitive science of music is the description of pitch structures in Western tonal-harmonic music. This includes musical scales, harmonics, and relations between musical keys. Music in many styles is organized around one or more stable reference tones (the tonic, in Western tonal music). Other tones differ in their degree of perceived stability, giving rise to a tonal hierarchy. Tones high in the hierarchy are remembered accurately, are heard as giving a sense of finality or closure, and are more expected within the tonal context—an effect that Janata *et al.* exploit in their tonality perception task. Keys that are considered closely related, in the sense that modulations (that



Mental key maps. (A) Unfolded version of the key map, with opposite edges to be considered matched. There is one circle of fifths for major keys (red) and one for minor keys (blue), each wrapping the torus three times. In this way, every major key is flanked by its relative minor on one side (for example, C major and a minor) and its parallel minor on the other (for example, C major and c minor). **(B)** Musical keys as points on the surface of a torus.

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is, shifts from one key to another) are relatively easy to effect, have similar tonal hierarchies and shared harmonies.

Geometric models, or maps, of these key relations that conform to descriptions in music theory have been generated by computational methods. One such key map in the shape of a torus or ring (*5*), and similar to that used by Janata *et al*. in their experiments, was obtained by training a self-organizing neural network model with experimentally quantified tonal hierarchies (see the bottom figure). This key map provides a visual display of an abstract mental model of key relationships. Results of experiments investigating how the sense of key develops and continuously changes can be projected onto the key map (*6*).

The strength of the Janata *et al*. work is that it brings together various techniques in an original combination. Their study probes the neural correlates of tonality perception in an effort to identify brain regions that respond to musically modulating sequences. In so doing, this study raises a variety of questions. Is the topography of the key map reflected directly in the cortical activation pattern? Alternatively, do the Janata *et al*. findings reflect more general processes of remembering and comparing tones? How are the activation patterns (in particular those of the ventromedial frontal area) observed by Janata and co-workers related to affective responses to music? One might expect sensory-related regions of the superior temporal cortex to be implicated in computing the relationships between tones that result in tonality mapping. However, it is still not known how the perceptual responses of the superior temporal cortex interact with the responses distributed across the activated brain regions reported by Janata and colleagues. Implicit learning of key musical structures may take place over a lifetime of listening to music, so it is possible that tonal maps become widely distributed over the brain. Regardless of the answers to these questions, cognitive neuroscience has benefited from the application of sophisticated cognitive models to explore the correlation between music processing and neuroanatomical regions of the brain.

References and Notes

1. P. Janata *et al*., *Science* **298**, 2167 (2002).
2. J. H. Kaas, T. A. Hackett, M. J. Tramo, *Curr. Opin. Neurobiol.* **9**, 164 (1999).
3. R. J. Zatorre, I. Peretz, *Ann. N.Y. Acad. Sci.* **930**, 193 (2001).
4. A. J. Blood, R. J. Zatorre, *Proc. Natl. Acad. Sci. U.S.A.* **98**, 11818 (2001).
5. P. Toiviainen, C. L. Krumhansl, *Perception,* in press.
6. See www.cc.jyu.fi/~ptoiviai/bwv805/index.html for a movie that shows how key strengths change over time as a Bach organ duet is played. The perceptual judgments of listeners (top) are compared with a computer model of key-finding (bottom).

PERSPECTIVES: MATERIALS SCIENCE

Nanocubes and Nanoboxes

Catherine J. Murphy

The visions of nanotechnology—smaller, faster, cheaper, smarter information-storage devices, energy sources, and medical devices in which the size of individual device elements approaches that of individual molecules—crucially depend on the ability to make and manipulate objects on the 1- to 100-nm scale.

The engineer's "top down" approach to making nanometer-scale objects is to carve them out lithographically from a substrate; the chemist's "bottom up" approach is to assemble them from molecular-scale precursors. On page 2176 of this issue, Sun and Xia (*1*) use the latter approach to show that simple chemical reactions in solution can produce silver nanocubes of controllable size in high yield. A simple, quantitative oxidation-reduction reaction of the silver nanocubes with gold salts results in hollow gold nanoboxes. The cubic faces of these nanomaterials are crystallographically well defined (*1*), an important feature for connecting these nanometer-scale elements into future devices.

Many applications envisioned for nanotechnology require nanometer-scale elements that are conducting or semiconducting. Inorganic materials such as metals and semiconductors have fundamental length scales in the 1- to 100-nm range (*2*, *3*). In metals, the mean free path of an electron at room temperature is ~10 to 100 nm (*2*). Hence, in a metallic particle with a diameter of ~100 nm or less, substantial deviations from bulk metallic properties are expected, and new size-dependent properties may emerge. For example, gold ceases to be a noble, unreactive metal: Gold nanoparticles 2 to 3 nm in diameter can catalyze chemical reactions (*4*).

The melting temperature of gold decreases drastically with size for spheres smaller than 20 nm (*5*). At diameters from ~10 to 100 nm, the spheres appear red, not gold, when well dispersed, as in stained glass (see the first figure). Nonspherical gold and silver nanoparticles absorb and scatter light of different wavelengths, depending on nanoparticle size and shape (*6*, *7*). Silver and gold nanoparticles have been used as sensors to detect analytes through surface-enhanced Raman scattering and other optical effects peculiar to the ~10- to 100-nm size range (*8*–*10*).

Synthetic chemical methods for making metallic nanoparticles of controlled size and shape are continually being improved. Metals such as silver, gold, cobalt, and platinum have been made into nanospheres, nanorods, nanowires, nanocubes, and nanoprisms through chemical reactions of precursors at room or slightly elevated temperatures (*6*, *7*, *11*–*13*), typically in the presence of a "directing" agent. Unfortunately, multiple shapes and sizes of nanoparticles are frequently produced in these reactions (see the second figure). Purification by centrifugation and size-selective precipitation (or tight control over reaction time) is then required to isolate pure products (*6*, *7*, *11*–*13*).

Red gold. Stained-glass window in Milan Cathedral, Italy, made by Niccolo da Varallo between 1480 and 1486, showing the birth of St. Eligius, patron saint of goldsmiths. The red colors are due to colloidal gold.

Control of size and shape was originally attributed solely to the presence of the "directing" agent, which functions as a hard or soft template (such as porous alumina membranes or micelles). It is now widely believed that preferential absorption of molecules and ions in solution to different crystal faces directs the growth of nanoparticles into various shapes by controlling the growth rates along different crystal axes (*11*, *14*, *15*). This view is shared by Sun and Xia (*1*).

In their study, the reaction to make silver nanocubes from silver nitrate takes place at ~150°C in a high–boiling point solvent (ethylene glycol), which also func-

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