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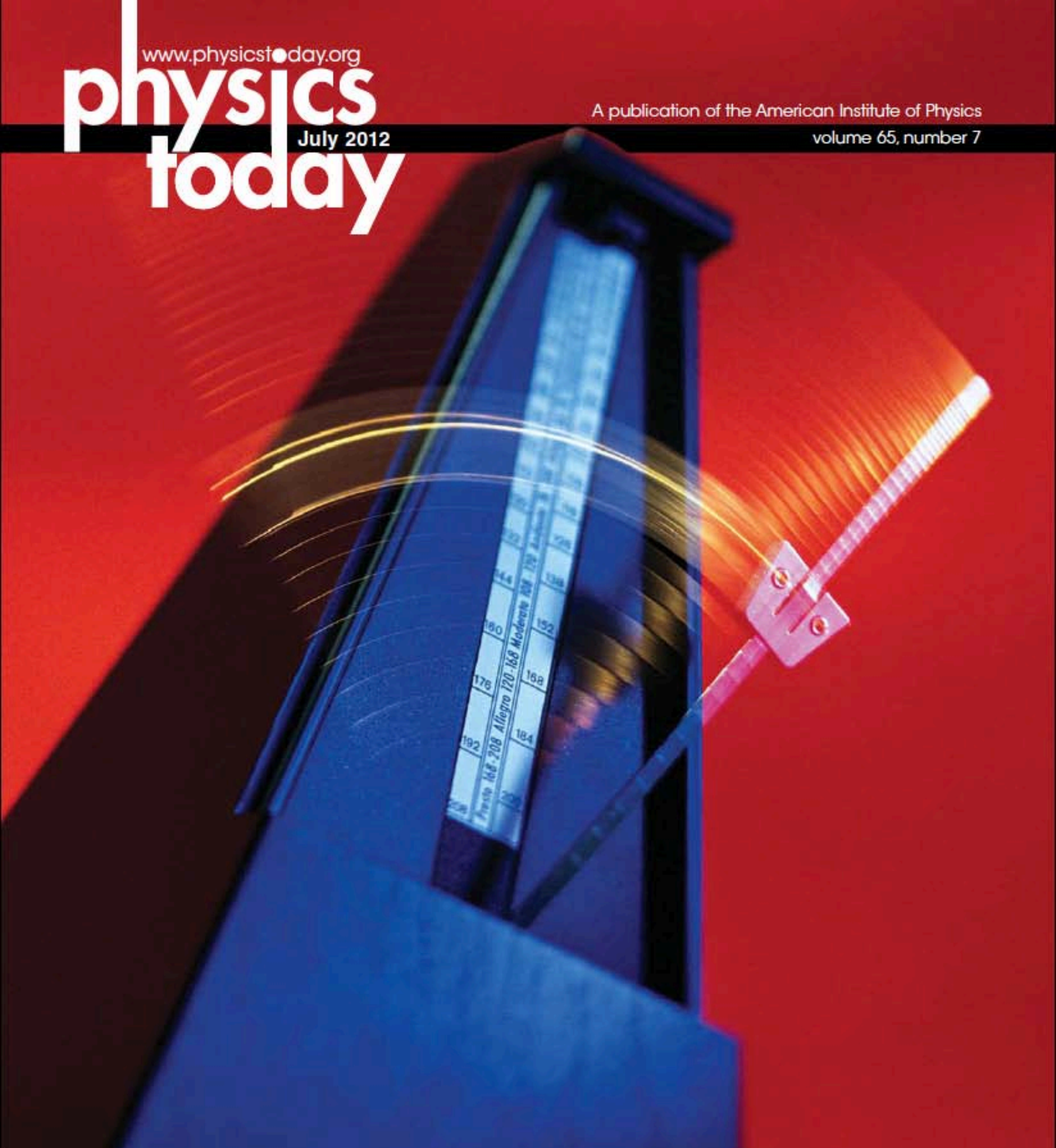

Off the beating path

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Musical rhythms: The science of being slightly off

Holger Hennig, Ragnar Fleischmann, and Theo Geisel

With a statistical understanding of our natural rhythmic imperfections, one can make computer-generated music sound more human.

Holger Hennig is a postdoc in the department of physics at Harvard University in Cambridge, Massachusetts. **Ragnar Fleischmann** is a staff scientist in the department of nonlinear dynamics at the Max Planck Institute for Dynamics and Self-Organization in Göttingen, Germany. **Theo Geisel** is director of the Max Planck Institute for Dynamics and Self-Organization, professor of theoretical physics at the University of Göttingen, and head of the Bernstein Center for Computational Neuroscience Göttingen.

Have you ever wondered why music generated by computers and drum machines sometimes sounds unnatural? One reason is the absence of small imperfections that are part of every human activity. Whatever your favorite music recording may be, rhythmic deviations accompany every single beat. The offsets are typically small, perhaps 10–20 ms. That's less than the time it takes for a dragonfly to flap its wings, but you can tell the difference in the music.

Audio engineers have known about the phenomenon for a long time. They will even add slight random deviations to a computer-generated musical piece to give it a more human feel, a procedure sometimes called humanizing. But the precise nature of the deviations made by humans playing complex rhythms has only recently been explored. Are the variations completely random from one beat to another, or are they correlated in a way that can be expressed by a mathematical law? To seek an answer, we turned to time series analysis, a technique widely used in chaos theory.

The beat generation

With a tip of the hat to Jack Kerouac, Allen Ginsberg, and the rest of the US writers who constituted the Beat Generation of the 1950s, let us consider an example of beat generation in a simple musical setting. A professional drummer from Ghana was recorded for more than five minutes during which he synchronized his drumming with metronome beats that he heard through headphones. Panel a of the figure shows the audio signal for five recorded beats, each separated from the following beat by ⅓ second, and indicates the musician's deviations from the metronome's rhythm. Panel b presents the deviations from the beat for the entire time series of 1030 beats. The mean deviation is −16 ms; the minus sign indicates that, on average, the drummer anticipated the metronome click.

A feature of panel b that immediately catches the eye is the existence of trends in the time series. For example, the deviations corresponding to beats 200–280 average to −29 ms, distinctly greater in magnitude than the mean deviation. For quite some time, the drummer played well ahead of the metronome. In contrast, about half a minute (90 beats) earlier, the drummer tended to play slightly behind the metronome clicks. Clearly, the deviations are not purely random. If a given beat is sounded ahead of the metronome, subsequent beats are also likely to be played early. Remarkably, though, correlations between beat deviations persist for several minutes. It is as if the human brain has an enduring memory for those deviations. The phenomenon is not limited to the temporal domain; it has also been observed when people reproduce spatial intervals.

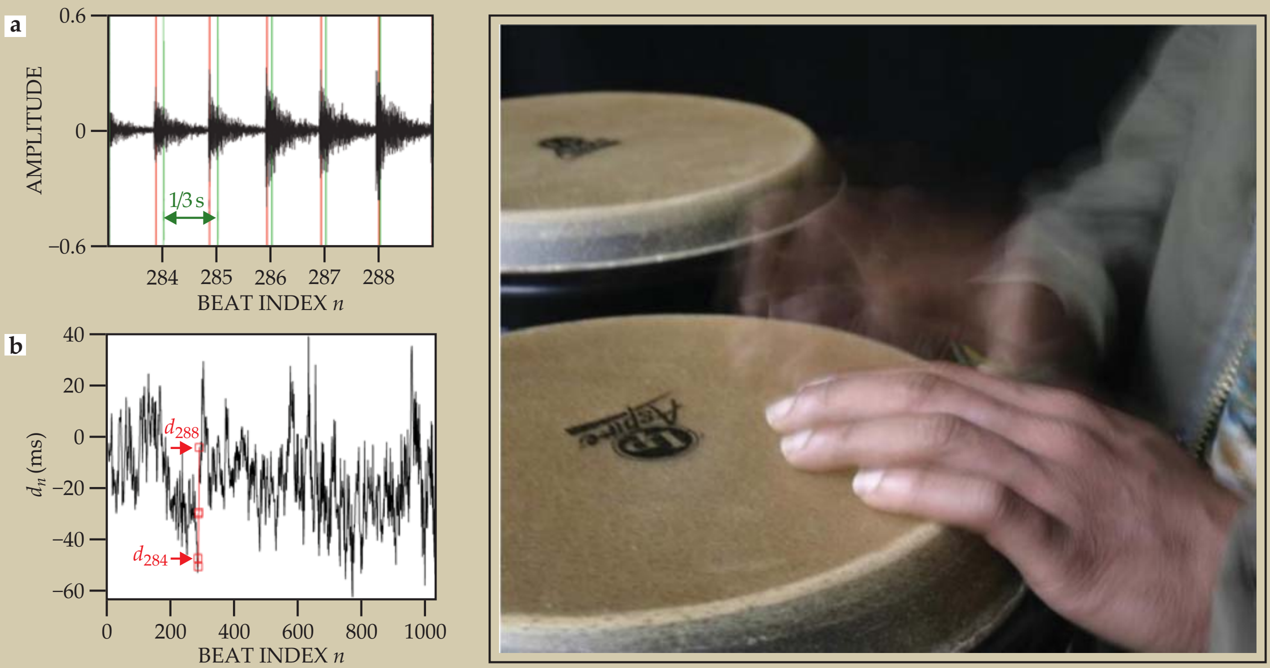
The influence of a beat deviation on its successors becomes less pronounced as the beats are farther apart in time. To characterize how quickly correlations die out, one can essentially express the time series as a sum of sines and cosines of various frequencies and determine the relative strength at each frequency f. The process of determining the resulting power spectrum is analogous to analyzing radio waves in the atmosphere by setting a radio to different frequencies and listening for how much power comes out at each.

In the case of the master drummer, the power spectrum S has the form $S \propto 1/f^{\alpha}$ with the dimensionless exponent $\alpha \approx 1$. If the exponent were to vanish, equal power would be generated at every frequency. In that case, the original time series is called white noise, and at every instant of time the signal is totally independent of its earlier values. For $0 < \alpha < 1$, the influence of a given beat deviation on a beat played at a time τ later decays with time like $\tau^{\alpha-1}$. (Technically, the statistical "influence" is defined by something called an autocorrelation function.) Evidently, for α near 1, memory decays slowly indeed, and as α approaches 1, memory tends to last forever. The same conclusion of long-term memory persistence results if α is a bit greater than 1; indeed, the time series is said to have long-range correlations (LRCs) if $0 < \alpha < 2$.

Long-range correlations are present when a drummer synchronizes with the beat of a metronome. But a ticking metronome is the simplest rhythm imaginable, so one can be forgiven for asking whether LRCs persist when musicians play more complex rhythms such as those in contemporary pop and rock music. It turns out that LRCs are inherent in all sorts of complex rhythms, generated with hands, feet, or voice, as long as the musician does not lose the rhythm completely.

What makes us tick

In the 1970s Richard Voss and John Clarke analyzed pitch fluctuations in classical and other types of music and also found LRCs there. Those LRCs, in Johann Sebastian Bach's compositions and in others', are statistical evidence that the melody at the end of the piece is related to those in other parts of the composition. That evidence for melodic memory makes sense: Bach, while he was composing, must have remembered the themes informing his piece and how they evolved. Earlier this year, Daniel Levitin and colleagues reported LRCs for the fluctuations of written note lengths in compositions of 40 different composers. Those and many other studies reflect the human preference for music with a



Feel the beat. The two plots shown here were obtained as the professional musician on the right played a hand drum while listening to regular metronome beats. **(a)** In this two-second time slice, green lines indicate metronome beats and red lines, determined from the absolute extremum of the audio signal of each beat, indicate the striking of the drum. **(b)** Over a period of 1030 beats, deviations from regular metronome beats (d_n) exhibit long-range correlations. The five deviations from panel a are marked with red squares. They illustrate how the drummer switches from playing ahead of the metronome at beat number 284 to playing almost simultaneously with the metronome at beat number 288.

balance of predictability and surprise. (White noise can be considered pure surprise.) Apparently, the memory inherent in LRCs is just right to sustain that balance.

What could be the source of our memory for deviations of only a few milliseconds in musical rhythms? Or, to put the question differently, what makes us tick on a millisecond time scale? Scientists have explored the question for decades, and the answer is still wide open. Strikingly, LRCs are entirely absent in individuals who frequently lose rhythm and try to regain it by following a metronome. That loss of LRCs may originate in a resetting of memory in the neurophysiological mechanisms that control rhythmic timing. Further research may help to unravel the neuronal mechanisms that make possible the amazing accuracy of human coordination on a millisecond time scale.

Perfecting imperfection

People often perceive perfectly timed computer-generated beats as artificial and lacking a human touch. Professional audio editing software therefore offers a humanizing feature that artificially generates rhythmic fluctuations. However, those built-in functions are essentially random number generators producing only uncorrelated fluctuations—white noise. The result is a rough ride: a rather bumpy, jerking rhythm. As an alternative approach to humanizing music, one could more closely imitate the human type of imperfection by introducing rhythmic deviations that exhibit LRCs.

To test how humanized music is received by listeners, our group, in collaboration with a recording studio, edited a pop song into two different versions—one humanized with white-noise fluctuations, the other humanized with LRCs. Asked for their preference, respondents significantly chose the LRC version over its white-noise counterpart. Listen for yourself: Audio examples of humanized music are available at http://www.nld.ds.mpg.de/~holgerh/gallery, which also includes some Bach pieces. To gather further data on what type of musical imperfection listeners favor, we have devised an online survey (accessible from the audio gallery on the website) in which both professional musicians and people without a musical background are welcome to participate.

The observation of LRCs in imperfect human musical rhythms demonstrates an approach frequently found in physics these days. The starting point is a complex system with abundant noise and elusive structure. In the case of human rhythm, the system is not just complex—it's a living musician. Nonetheless, one can seek mathematical laws that shed light on the underlying mechanisms governing the system. In the case of the musician, a power law reveals an aspect of human coordination.

To err is human. But isn't that part of the complexity and beauty of human activity? Yes—even more if the human happens to be a really good drummer.

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Additional resources

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▶ D. L. Gilden, T. Thornton, M. W. Mallon, "1/*f* noise in human cognition," *Science* **267**, 1837 (1995).
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