However, these structured materials can only function at low temperatures (below 500°C). Integrating twisted carbon nanotubes with metasurfaces could be a new way to achieve bright thermal emitters with high purity of circular polarization that can operate at high temperatures.

The spinning heat radiation from both metasurfaces and twisted carbon nanotubes obeys Kirchhoff's law of thermal emission (*8*), which states that an electromagnetic wave absorbed by an object is equal to the amount of radiation emitted at thermal equilibrium. This law connects closely to Einstein's A and B coefficients that relate absorption of light to the probabilities of absorption, spontaneous emission, and stimulated emission from a noninteracting ensemble of emitters (*9*). These relations can quantify the brightness and spectrum of the circularly polarized thermal radiation. However, the angular momentum of thermal radiation, which is related to rotational behavior of heat waves, is overlooked in these traditional viewpoints. For example, a torque that causes nanoscale objects to rotate can be generated from the angular momentum of thermal radiation (*10*). The spinning heat radiation could also transfer giant angular momentum between objects with a distance closer than the wavelength of radiation. This could allow near-field radiative energy transfer, which is promising for thermal management in microelectronics and radiative cooling devices.

Further, integrating twisted carbon nanotube–based emitters of Lu *et al.* into on-chip systems could produce nanoscale functional devices with precise control of thermal radiation. The distinct polarization texture of these emitters is particularly desirable for defense applications. For example, a passive infrared beacon can be made of the twisted filaments because the background thermal emission from natural objects has a nearly vanishing degree of circular polarization. ■

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NEUROSCIENCE

Aged neurons don't register energy need

Neuronal activity and mitochondrial gene expression become decoupled in aged mice

By **Deniz Bingul** *and* **Scott F. Owen**

As highly efficient energy factories of the cell, mitochondria generate adenosine triphosphate (ATP), primarily through the process of oxidative phosphorylation (OXPHOS). In the aging mammalian brain, mitochondrial metabolism begins to break down, with widespread consequences for neuronal and circuit function. Degradation of the OXPHOS pathway can drive oxidative stress and mitochondrial damage during aging (*1*). Yet the process by which OXPHOS activity becomes degraded and impairs mitochondrial efficiency has remained unclear. On page 1363 of this issue, Li *et al* (*2*) demonstrate that neuronal excitation increases mitochondrial gene transcription, a process that diminishes with age in mice. Remarkably, restoration of excitation-transcription coupling in mitochondria improves memory function, identifying a potential route to reverse age-related cognitive decline.

"...healthy mitochondria scale their gene expression when they sense a neuronal 'rush hour.'"

Consider the experience of visiting a favorite coffee shop during the morning rush hour. To handle increased demand, the baristas open extra registers. Imagine, however, what would happen if one or more of the registers fail: Orders back up, and people are made late or leave empty-handed because the shop cannot scale its operation to support the increased demand. Neurons similarly scale resources during periods of high network activity. Synaptic plasticity and homeostasis, two fundamental mechanisms of learning and memory, markedly increase metabolic demand (*3*, *4*). Failure to calibrate brain energetics to meet this demand can disrupt these crucial functions. Energetics and cognition can both become impaired in the aging brain (*1*, *3*, *5*), yet it is unclear how aging constrains the dynamic regulation of brain energetics to influence cognition.

Synaptic plasticity and homeostasis engage a process called excitation-transcription coupling (E-TC). The canonical nuclear E-TC pathway is initiated by activity-driven calcium influx into the dendrites, soma, or nucleus of a neuron, resulting in the phosphorylation of calcium-calmodulin–dependent protein kinase II (CaMKII). This leads to phosphorylation of Ca^{2+}/ cyclic adenosine monophosphate (cAMP) response element–binding protein (CREB) and subsequent transcription of genes vital for learning and memory (*6*–*10*).

Mitochondria efficiently sequester calcium that enters neurons during periods of high activity, making them gatekeepers of E-TC (*9*, *10*). Given that mitochondria have their own genome, Li *et al.* reasoned that a parallel E-TC pathway may regulate the expression of mitochondrial genes. They found that mitochondria do indeed respond to calcium influx by increasing the expression of mitochondria-encoded genes necessary to sustain increases in neuronal activity (see the figure). When the authors selectively inhibited activity-dependent calcium influx or mitochondrial CaMKII signaling, the expression of mitochondria-encoded OXPHOS genes decreased. Just as the coffee shop scales the number of open registers to meet demand during rush hour, healthy mitochondria scale their gene expression when they sense a neuronal "rush hour."

Strikingly, Li *et al.* found that mitochondrial calcium influx encodes changes in neuronal activity less efficiently with age. To demonstrate this directly, they developed a mitochondria-targeted calcium sensor to record mitochondrial calcium influx in the primary somatosensory cortex during whisker stimulation in young and old mice. This influx was attenuated in old mice, suggesting that there is a mismatch between mitochondrial energetics and neuronal activity in aging.

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What are the consequences of impaired calcium signaling for synaptic homeostasis in changing network environments? Canonically, neurons up- or downscale synaptic strength and excitability in response to prolonged changes in activity, a process essential for maintaining stable neuronal activity levels when synaptic weights are altered during learning, development, or aging (*11, 12*). In a key set of experiments, Li *et al.* showed that activity-dependent engagement of the mitochondrial transcription factor CREB regulates this adaptation. Inhibiting mitochondrial CREB ($CREB_{mito}$) in cultured excitatory neurons impeded mitochondrial gene expression, reduced the amplitude of excitatory synaptic currents, and decreased surface expression of the GluA1 subunit of glutamate receptors after drug-induced increases in network activity. As a result, although neurons responded faster to persistent changes in synaptic transmission, they were slower to return to baseline after stimulus withdrawal.

"...there is a mismatch between mitochondrial energetics and neuronal activity in aging."

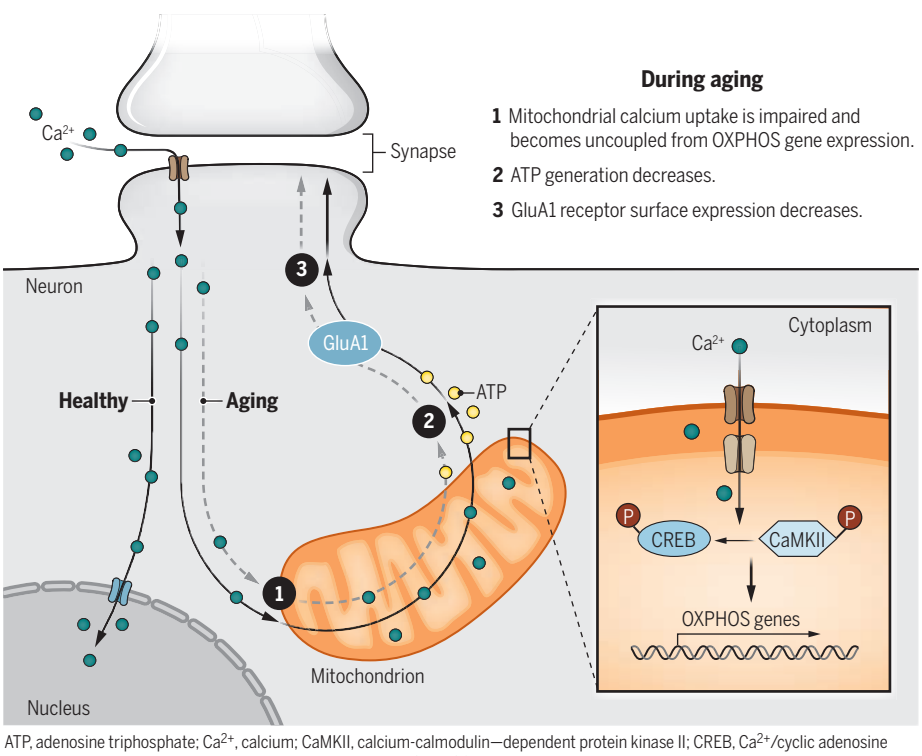
Inhibition of $CREB_{mito}$ activity was also associated with a smaller pool of synaptic ATP. This is problematic for neurons because homeostatic adaptation is energetically expensive. Using an ATP sensor they developed, Li *et al.* found that expression of GluA1 at the cell surface consumes ATP. Impaired $CREB_{mito}$ activity and insufficient ATP reserves therefore compromise the ability of neurons to maintain synaptic strength within a dynamic range. Moreover, restoring ATP levels by overexpressing cytosolic creatine kinase to regenerate ATP rescued GluA1 surface expression.

Li *et al* further tested the cognitive consequences of losing this dynamic range in mitochondrial signaling. Using new mitochondria-localized CREB sensors, they found that activity-dependent recruitment of $CREB_{mito}$ is abolished in old mice. To model this in vivo, the authors inhibited $CREB_{mito}$ in excitatory neurons of old mice, which impaired spatial and fear memory and blocked mitochondrial DNA expression after neuronal activation by contextual fear conditioning. Notably, these behavioral deficits were rescued by expressing a constitutively active CREB variant in old, CREB-inhibited mice.

Through an impressive combination of innovative tools, clever physiology, and compelling behavior experiments, Li *et al.* provide key insights into mitochondrial biology in the aging mammalian brain. The findings raise the possibility of identifying targets for age-related neurocognitive disorders associated with mitochondrial dysfunction, including Alzheimer's and Parkinson's diseases (*3*). The study also inspires questions about how E-TC might generalize to non-neuronal cell types and interact with other metabolic pathways. For example, many non-neuronal (glial) cells sense glutamatergic activity through glutamate receptors, whose activation triggers glial calcium transients (*13*). Activity-dependent changes in calcium signaling might similarly regulate gene expression in glial mitochondria to shape metabolic cooperation between glia and neurons. Furthermore, the reduction of OXPHOS gene expression may also cause compensatory shifts to other metabolic strategies in the aging brain. Whether energetic shuttles, such as those proposed to exist between neurons and astrocytes, may be recruited as a compensatory mechanism in aging remains to be explored (*14*, *15*). The opportunity to investigate these questions, which build on the fundamental mechanisms elucidated by Li *et al.*, suggests that a rush hour is coming for the study of mitochondrial aging—time to open more registers. ■

Mitochondrial bioenergetics in aging neurons

During periods of high activity, mitochondria sequester calcium that enters mouse neurons. This triggers mitochondrial CaMKII and CREB activity, which leads to transcription of OXPHOS genes necessary for ATP production that supports surface expression of receptors at the synapse. With aging, this pathway is less efficiently engaged by mitochondrial calcium uptake, impairing OXPHOS gene transcription, ATP output, and receptor surface expression.



ATP, adenosine triphosphate; Ca^{2+}, calcium; CaMKII, calcium-calmodulin–dependent protein kinase II; CREB, Ca^{2+}/cyclic adenosine monophosphate (cAMP) response element–binding protein; OXPHOS, oxidative phosphorylation; P, phosphorylation.

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