

tion of thin films. The main challenge of implementing additive manufacturing to such devices is formulating an ink that promotes sufficient bonding between its constituents upon drying. Additionally, it is highly unconventional to fine tune the functional properties of semiconductors after printing.

For an efficient thermoelectric cooler, achieving high electrical and low thermal conductivity are required. Both these properties are dictated by a material's microstructure—the atomic arrangement that consists of crystalline grains, interfaces, and defects. Length scale of individual grains and spatial dimension of defects within a crystal affect the mobilities of charge carriers and phonons (quasiparticles associated with atomic vibration). Good interfacial bonding between grains is needed to maximize electrical conductivity, whereas a certain density of defects is required to scatter phonons to reduce thermal conductivity (6, 7). Although these two conditions are seemingly incompatible, charge carriers and phonons generally have a different mean free path—the average distance a particle travels without a collision. Thus, engineering a material's microstructure could decouple the two conditions to achieve desired functionality of a thermoelectric cooler (8). Extrusion-based 3D printing inevitably results in porous structures because of the inherent gap between the deposited components. Such material has air pockets that scatter phonons, resulting in low thermal conductivity (4). By contrast, achieving adequate electrical conductivity is challenging because of the reduced interfacial areas between the grains. Thus, coherent networks of semiconductor grains should be formed by carefully controlling the microstructure of porous thermoelectric coolers, which has not been obtained using 3D printing methods.

Xu *et al.* report additively manufactured components of a thermoelectric device with a record-high cooling temperature gradient of 50°C in an ambient environment. The authors demonstrate judicious microstructure engineering of 3D printed parts using a material's inherent properties and additives in the ink formulation (see the figure). The two leading n-type (negative) and p-type (positive) semiconductors used for thermoelectric cooling—silver selenide (Ag<sub>2</sub>Se) and bismuth antimony telluride [(Bi,Sb)<sub>2</sub>Te<sub>3</sub>], respectively—were successfully printed. Colloidal suspensions were used as inks to promote interparticle bonding at low temperatures without an applied pressure. The printed materials exhibited a porous

structure with micrometer-sized grains and abundant defects.

Engineering the microstructure of n-type silver selenide is elegant in its simplicity. Xu *et al.* exploited a phase transition at 130°C to a superionic phase that consists of more freely moving atoms within a solid lattice. The increased mobility of silver atoms formed coherent interfaces between grains with a large density of defects, which is ideal for low thermal conductivity and high electrical conductivity. In the case of bismuth antimony selenide, the low melting temperature of bismuth nanoparticles acted as a solder to enable a solid network within the 3D printed components during the mild heat treatment. Liquid bismuth also accelerated the reaction with the molecular antimony telluride additive (Sb<sub>2</sub>Te<sub>4</sub>), such that the composition of the interfaces matches closely that of bismuth antimony selenide grains. This reaction produced a high density of defects to scatter phonons. Further, Xu *et al.* included the xanthan gum binder in the ink to reinforce mechanical properties of as-printed semiconductors.

The findings of Xu *et al.* highlights how microstructure engineering by carefully formulating printer ink can make a high-performance functional material. Optimizing constituents of the ink and deposition parameters could potentially print materials that are close to the benchmark quality of crystalline layers with precise arrangement of atoms. This would enable fabrication of high-quality semiconductors with the benefits of 3D printing for simplicity, fast production speed, and efficiency.

The work of Xu *et al.* demonstrates that a highly porous thermoelectric cooler can perform as well as its dense thin-film counterparts. The economic cost of 3D printing makes it desirable for fabricating semiconductor devices beyond thermoelectric cooling. The ability to precisely control porous microstructure could be advantageous to other energy applications that can tolerate or require high surface areas. These include electrocatalysts, fuel cells, batteries, and supercapacitors, from liquid-borne materials, such as molecular complexes and colloidal nanoparticles (9). ■

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## NEUROSCIENCE

# An innate drive to save a life

## In mice, two brain regions drive the impulse to revive an unconscious companion

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People who witness someone collapse and who subsequently perform cardiopulmonary resuscitation (CPR) report that they intervene because they intuitively understand that the person would otherwise die (1). Humans are not alone in this instinct. Animals as diverse as elephants [*Loxodonta africana* and *Loxodonta cyclotis* (2)], chimpanzees [*Pan troglodytes* (3)], and dolphins [*Tursiops truncatus* (4)] can recognize and intervene by touching, nudging, and even carrying an incapacitated individual. On pages 843 and 842 of this issue, Sun *et al.* (5) and Sun *et al.* (6), respectively, provide information on the neurobiology underlying this impulse. They report that mice (*Mus musculus*) have an instinct to revive an unresponsive mouse and identify two distinct brain regions that are crucial for this behavior. These findings add to the evidence that an impulse to help others in states of extreme distress is shared by many species and highlight neural mechanisms that drive instinctive rescue.

Innately driven social behaviors are those that are not explicitly taught but instead seem to preexist in the brain, ready to be triggered by the right circumstance (7). For example, a newly hatched duckling or gosling will exclusively follow the first moving entity it sees, a form of social bonding critical for offspring survival. This process, called imprinting, is mediated by *N*-methyl-D-aspartate (NMDA) receptors in the intermediate and medial mesopallium of the brain and is so strong and immutable that once imprinting has occurred, the baby bird is unable to imprint on anyone else (8).

Sun *et al.* and Sun *et al.* addressed whether such innate predisposition for specific social actions extends to how an animal responds to another's apparent distress. Both groups

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A bystander mouse bites an incapacitated mouse's face and tongue, pulling the tongue out of the mouth and enlarging the unconscious animal's airway. This behavior often facilitated recovery.

found that mice increased the time they spent investigating and grooming another mouse if it was rendered unresponsive by either a sedative (5) or an anesthetic (6). As the drugged animal fell deeper into an unresponsive state, the bystander transitioned from more passive social investigation, such as sniffing, to increasingly intense grooming directed at the face. These bystander mice rarely groomed the faces of awake mice or asleep (but not drugged) controls.

Sun *et al.* (6) showed that facial grooming was particularly focused on pulling and biting at the incapacitated animal's tongue. Approximately half the time, the bystander animal was able to pull the other animal's tongue out of its mouth, successfully enlarging the unconscious animal's airway (see the photo). Furthermore, when a foreign object was placed in the incapacitated animal's mouth, the bystander mouse removed it before continuing to manipulate the tongue. These behaviors are reminiscent of how humans are taught to clear the airway of an unconscious individual during CPR (9).

It is easy to anthropomorphize these resuscitation-like behaviors as a rodent's approximation of CPR, but do they facilitate recovery? Sun *et al.* (5) found that incapacitated animals that received face-directed grooming from a bystander twitched more often and, critically, both Sun *et al.* and Sun *et al.* found that they regained consciousness more quickly than incapacitated animals that were alone. Furthermore, a separate, recent study reported that tongue biting and dragging promotes arousal in anesthetized mice through a direct tongue-brain circuit (10). Notably, in the studies by Sun *et al.* and Sun *et al.*, the bystander animals reduced the amount of face-directed grooming as the

drugged animals regained consciousness, ultimately reverting to sniffing and other interactive behaviors that are typical of awake animal pairs. Therefore, face-directed grooming behaviors seem to aid recovery of the incapacitated mouse and to be implemented only when bystander animals sense that their intervention is needed.

To investigate the neuronal mechanisms underlying the observed resuscitation-like response, Sun *et al.* (6) screened candidate regions in the brains of bystander mice for increased expression of the immediate early gene *Fos*, which is a marker for neuronal activation. This screen identified the paraventricular nucleus (PVN) of the hypothalamus and the medial amygdala as regions of interest. *Fos* expression was particularly high in the subpopulation of PVN neurons that produce oxytocin, a neurohormone that is important for social behavior in organisms ranging from worms to humans (11). In rodents, oxytocin promotes consolation and empathy-like behaviors, which prompted Sun *et al.* (6) to focus on the potential role of these neurons in mediating resuscitation-like behaviors. By contrast, Sun *et al.* (5) focused their efforts on the medial amygdala, which is a part of the brain critical for a range of innate social behaviors. These behaviors include allogrooming, a form of comforting, gentle touch directed toward a distressed animal (12).

Despite examining two distinct brain regions, Sun *et al.* and Sun *et al.* obtained very similar results. In bystander mice, subsets of medial amygdala and oxytocinergic PVN neurons showed patterns of activity that discriminated between incapacitated and awake individuals. This discrimination was also evident in the collective activity of all recorded

neurons in either region, implying that the brain might encode information about incapacitated states by using strategies that range from the output of individual, stimulus-responsive neurons to the summated output of entire populations of neurons. Furthermore, experimental inhibition of neurons in the medial amygdala or oxytocinergic neurons in the PVN diminished resuscitation-like behaviors, whereas activation of either enhanced them. This indicates that both brain regions are critical for promoting rescue responses.

Why might neurons in two distinct regions contribute to the same behavior? Oxytocinergic neurons in the PVN have diffuse projections throughout the brain, including a direct connection with neurons in the medial amygdala (13). The release of oxytocin from such projections might increase the signal-to-noise ratio of neuronal activity relating to specific social cues and in turn modify the perceived importance of those cues (13). For example, oxytocin release in female mice who have recently given birth heightens their focus on distressed pups, promoting the retrieval of those pups to the nest. This occurs because oxytocin enhances neural responses to pup calls in the left auditory cortex (14). Through mechanisms such as this, oxytocin and other neuromodulators such as dopamine and norepinephrine have been proposed to shape information processing in the brain in a dynamic way to promote distinct cognitive and behavioral functions (15).

In the context of behavioral responses to an unresponsive mouse, a specific neuromodulatory state, generated in part by PVN oxytocinergic neurons, might enable optimal information processing in key regions, including the medial amygdala, to enhance recognition of incapacitation and/or promote a rescue response. Experimental manipulation of oxytocin release specifically in the medial amygdala and other target regions will be required to test this hypothesis. ■

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