comparable with that of silicon. The same strategy that allows a bumper to adsorb impact when hitting an obstacle allows the fibers embedded in a soft matrix (composed of an elastomer) to inhibit crack propagation when the device is stretched. Remarkably, after optimization of the process, this complex geometry can be obtained via a surprisingly low-cost procedure. Upon mixing, the components spontaneously assemble in their final shape and remain stable for a time scale much longer than those of technological interest.

These results are not the first case in which unusual material properties, or extraordinary applications, are associated with confinement effects. Wang *et al.* discovered that an adequately processed 20-nm-thin layer of poly(ethylene oxide) (PEO) has the same gas permeability of a 4-mm-thick film of the same polymer (*10*). Careful analysis of the morphology of these nanofilms revealed that the unexpected two-orders-of-magnitude increase in barrier properties arose from improved crystal ordering upon confinement. Permeation in bulk PEO is possible via the many defects in the crystalline structure. The nanostructure films instead resemble a jigsaw puzzle of impermeable large crystals that allows diffusion of gas molecules only through the rare interfaces among pieces.

The path that brought about the development of 100% stretchable electronics is quite different from this membrane work. Xu *et al.* actively used the insights gained from fundamental research on confinement effects of polymers to solve a long-standing problem of applied electronics. Similar strategies for other applications should be able to exploit the broad set of known nanoconfinement effects. For example, the intrinsic manifestation of nonequilibrium effects in nanoconfined polymers could be used to fabricate systems that reproduce active membrane motion (*11*) and other cell activities. ■

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PHOTO: MERLIN D. TUTTLE/SCIENCE SOURCE

Proportional perception by the nectar-feeding bat *Glossophaga commissarisi* can explain why the flowers they feed on evolve to have intermediate sugar concentrations.

EVOLUTION

Perception drives the evolution of observable traits

Bats choose flowers on the basis of nectar volume and concentration, affecting how the flowers evolve

By **Hamilton Farris**

The phrase "perception is reality" is used in many contexts but is often not true. For example, human inability to perceive ultraviolet light does not negate its reality. Nevertheless, perception can cause reality to evolve. This is the insight of the study by Nachev *et al.* on page 75 of this issue (*1*). The authors integrated field and laboratory experiments with computer simulations to explain how perceptual mechanisms in a pollinator—a bat—can cause the evolution of counterintuitive traits in flowers.

The appearance, sound, taste, and smell of an organism are determined by the perceptual abilities of the observer. This means that the perceptual abilities of observers are likely to have played a role in the evolution of countless traits across species. For example, morphological traits such as those used in the visual camouflage of prey species are under selection from predators with particular visual abilities, resulting in the evolution of traits that the predators perceive to be less distinguishable from the inedible background (*2*). Thus, understanding perceptual abilities, including the ability to notice differences in stimuli, is critical to understanding the evolution of observable traits.

Are there general perceptual rules that could be used to explain and predict selection on such traits? It has been known since the 1800s that for a constant or linear change in the physical magnitude of a stimulus, humans do not experience an equivalent change in perception (*3*). For example, if the number of bulbs lighting a room is increased from one to two, an observer is likely to notice the difference in brightness. If, however, the increase is from 50 to 51 bulbs, many observers will struggle to notice the change, even though the absolute change is the same in both cases. In fact, to be noticeable, the difference between two stimuli must be not constant but rather proportional to its physical

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magnitude (*4*), which is historically called the Weber fraction (*3*). In the example above, an increase in bulbs in the second condition that would be proportional to the first is from 50 to 100 bulbs.

Thus, as a stimulus increases in physical magnitude, the just-noticeable difference also gets larger. In other words, using proportions to compare ever larger stimuli makes it more difficult to perceive stimulus changes; as a large stimulus increases, perception of its size or value appears to remain the same.

The use of proportional perception is not limited to humans. In other animals—including insects, birds, amphibians, and nonhuman mammals—perception of visual, acoustic, chemical, magnetic, tactile, and electrical stimuli is also proportional (*5*). As evidence for the universality of proportional perceptions accumulates, we must determine how it drives the evolution of observable traits. This is important because one possible limit on the evolution of ever more exaggerated traits (such as sexual signals included in plumage and song) is the diminishing return on increasing the size of already large traits; observers will be unable to perceive differences unless the change is proportional to their large magnitude (*6*). Such a check on directional selection has been inferred from data showing proportional perception (*7*). Furthermore, when a trait is so large that it becomes too difficult to produce a perceivable change, the observer may evaluate a different trait that is still within its distinguishable range.

Proportional perception may limit trait evolution in many ecological contexts. In their study, Nachev *et al.* (*1*) investigate how perception that is based on proportions affects the evolution of traits in flowers that attract pollinators. They designed field experiments to determine how flowers evolve dilute nectar, even though pollinator bats prefer higher concentrations of sugar. The authors allowed bats to visit computer-controlled artificial flowers with virtual genomes that varied in their nectar production. Thus, although the bats were real pollinators, they were selecting for new generations of virtual "seeds" with different genomic profiles for nectar production. The resulting artificial flowers evolved intermediate nectar concentrations rather than an ever more syrupy juice.

There are at least two stimuli that the bats could be evaluating: the sugar concentration and the overall nectar volume. The magnitudes of both concentration and volume can, however, change as a result of consumption by bats. These changes can affect which stimulus is more easily distinguished. Nachev *et al.* used computer simulations and laboratory experiments to understand how these stimuli and their changes contribute to the evolution of intermediate nectar concentrations. They show that the field results can only be confirmed if bats judge the stimuli according to proportions. The reason is that differences in high nectar concentrations and larger volumes are more difficult to discriminate than are the same absolute differences in low nectar concentrations and small volumes.

Decisions based on the two stimuli are not necessarily coupled, however. The authors show that when proportional perception makes it difficult to distinguish one stimulus dimension because its magnitude is too high, bats may choose flowers according to the other stimulus dimension. That is, when distinguishing high concentrations is too difficult, the bats may choose flowers on the basis of nectar volume, leading to the evolution of diluted nectar.

Nachev *et al.*'s study successfully integrates psychophysics (measuring the psychological experience of a physical stimulus) and evolutionary biology. This integration is long overdue; Darwin wrote in 1872 that inherited variation in certain traits depends "on the powers of perception, taste, and will" of observers (*8*). Models of trait evolution that are driven by the ability of individuals to choose or distinguish characters (*9*) would benefit from definitive measurements of perceptual systems. Such data would improve our understanding of how perception influences trait evolution.

In concert, a comparative approach in psychophysics could determine which perceptual mechanisms are universal and which have evolved specializations to mediate particular decisions in particular species (*10*). For example, even though proportional perception has been studied for more than a hundred years, it is still unknown how selection alters those proportions in different species and whether the underlying neural mechanisms are shared. The study by Nachev *et al.* should serve as a model for how such interdisciplinary work can lead to novel and more complete explanations of trait evolution. ■

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PHYSICS

The fragility of distant Cooper pairs

The discovery of superconductivity in bismuth is a challenge to standard theory

By **Kamran Behnia**

The first superconductor was discovered in 1911, when elemental mercury was cooled below the helium liquefaction temperature. Suddenly, it ceased to show any resistance to the flow of electricity. Soon after, it became clear that some metals become superconducting upon cooling, and some do not. Half a century or so later, a quantum-mechanical theory of superconductivity was conceived by Bardeen, Cooper, and Schrieffer (BCS). On page 52 of this issue, Prakash *et al.* (*1*) report the surprise discovery of superconductivity at extremely low temperatures in bismuth, a familiar and extensively documented metal (*2*). The results mark a new episode in the history of superconductivity.

"The lattice structure [of Bi] has modified the familiar electron…beyond recognition."

The central idea in BCS theory is the pairing up of electrons. The condensation of these pairs to form a macroscopic wave function then turns the metal into a superconductor. A phase transition transforms a liquid of individual electrons (which retain their distinct quantum numbers) into a superfluid condensate (where individual electrons cease to exist). The main requirement for pairing to occur is an infinitesimal attraction between electrons, despite their intrinsic repulsion. Attesting to the fertility of this concept is the role it has played in explaining the superfluidity of ^{3}He (*3*) and

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Perception drives the evolution of observable traits

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Editor's Summary