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.  

REFERENCES


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 3He (3) and

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in describing neutron stars (4) (see the figure, top panel). As an effective theory of metallic superconductivity, BCS theory gives a satisfactory account of physical properties. Even when it is found near another competing instability and even in the presence of a strong correlation among electrons, the superconducting state has been found to be a condensate of Cooper pairs, sometimes with nontrivial symmetry.

However, despite its glorious history, and unusually for a celebrated scientific theory, BCS theory has been effectively impotent in predicting new superconducting materials—a pursuit that has remained an empirical enterprise. A mystery surrounds the attractive interaction leading to the formation of Cooper pairs. In the case of common superconductors, exchanging phonons between electrons can generate such an attraction. The vicinity of a competing order offers other pairing possibilities such as those involving the spin of electrons. It is fair to say that while the existence of Cooper pairs has been demonstrated beyond a reasonable doubt, save for the simplest superconductors, the identification of the binding glue remains a difficult, and open, question.

The discovery of ultralow-temperature superconductivity in bismuth provides a new challenge. The lattice structure has modified the familiar electron to complex Bloch waves beyond recognition (see the figure, bottom panel). Each mobile charge carrier in bismuth occupies a volume containing $10^5$ atoms. Half of the carriers are hole-like and the other half, electron-like. The bare mass of electron-like carriers is a thousandth of the bare electron mass along one orientation. The spin and the momentum are locked to each other, and therefore one cannot separate the spin and the spatial components of the wave function. The quantum numbers defining each fermion are thus quite different from those of electrons in a vacuum.

What drives pairing in the case of bismuth? One may think that the phonon-mediated scenario of pairing would have no difficulty in explaining superconductivity at such a low temperature. After all, amorphous bismuth and pressurized bismuth (both more atomically packed than the rhombohedral crystal found at ambient pressure) are ordinary superconductors with a decent critical temperature. Why should one care about the 0.5-mK instability of this strangely dilute metallic system?

The caveat comes from an important detail in BCS theory. An infinitesimal attraction between fermions would destabilize the Fermi sea, as long as it only restricts itself to a narrow thickness around the Fermi level (5). In almost all superconductors, this restriction is readily provided by the fact that the Debye temperature (the typical energy of phonons) is much smaller than the Fermi energy. But in bismuth, the

discovered by cooling arsenic and antimony below 15 mK, the lowest temperature attained in previous studies (11).

REFERENCES

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The fragility of distant Cooper pairs
Kamran Behnia (January 5, 2017)

Editor's Summary

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