

The special nature of the single-electron wave functions required for topological insulators arises naturally in insulators that have small band gaps and strong spin-orbit coupling because they contain heavy atoms. Experimental evidence for the strange surface states was found shortly after their prediction (8) in transport measurements in a device containing a thin layer of HgTe forming a “quantum spin Hall insulator,” the two-dimensional version of the topological insulator (9). Shortly thereafter, it was realized that topological insulators could form in three dimensions (6), and the heavy semimetal bismuth, alloyed with antimony to turn it into a small-gap insulator, was identified as a candidate (5). Transport measurements on the surface of a crystal are very difficult, but angle-resolved photoemission can image the surface electron bands directly. Last year, Hsieh *et al.* (10) showed that there are an uneven number of surface bands crossing the Fermi energy.

Spin-orbit coupling lies at the heart of the topological insulator, but how does this relate to the effects of relativity discussed in the context of a MnSi skyrmion lattice? Electrical fields are present at the Bi_{1-x}Sb_x crystal surface, but these will not give rise to magnetism. However, under the influence of the topological bulk, the surface spins do not order in physical position space, but rather in the space formed by the wave vectors of the quantum waves describing the electrons moving on the

surface. This two-dimensional wave vector space repeats periodically, and because the surface is metallic, it contains a periodic array of Fermi “surfaces” enclosing the regions with occupied states.

When the bulk is a topological insulator, the remarkable coincidence is that the skyrmion lattice described by Mühlbauer *et al.* forms an acceptable cartoon of what this “magnetism in wave vector space” looks like. The skyrmions are now regions of occupied states, and their rims are the Fermi surfaces. The spins at the Fermi energy are precisely oriented as the whirls formed by the “golden” spins.

However, the cartoon is not a literal description as electron energies move away from the Fermi energy. The whirl-like arrangement of the Fermi surface spins should actually persist both for the occupied and unoccupied states, with the spins slowly vanishing upon moving away from the Fermi surface. Using spin-resolved photoemission, Hsieh *et al.* observe precisely this “wave vector space magnetism,” which is direct evidence that Bi_{1-x}Sb_x is a topological insulator.

The discovery by Mühlbauer *et al.* that spins can order in the form of a lattice of topological particles confirms that skyrmions indeed can behave like atoms and opens up new avenues of research related to electrical transport, especially in relation to the very strange metallic states found in MnSi when it is put under pressure. Hsieh *et al.* show that a

simple alloy of bismuth and antimony allows us to hold something very nonintuitive—a macroscopic quantum entangled state—in the palms of our hands, and the theorists continue to suggest new ideas for experimental study. The electrodynamics of topological insulators is also quite strange: When an electrical charge is brought to the surface, it will bind automatically to a magnetic monopole formed in the bulk, and this “dyon” should behave like a particle with fractional quantum statistics (11). Alternatively, when a superconductor is brought into contact with a topological insulator, its magnetic vortices are predicted to turn into particles that can be used for topological quantum computing (12).

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NEUROSCIENCE

Pains and Pleasures of Social Life

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Life is full of complex social events such as being accepted or rejected, treated fairly or unfairly, and esteemed or devalued by others. Our responses to these events depend primarily on our psychological interpretation of them, in contrast to events like spraining an ankle or eating chocolate, for which our responses seem more dependent on the physical acts themselves. Nevertheless, our emotional responses to these psychological events rely on much of the same neural circuitry that underlies the simplest physical pains and pleasures. On page 937 of this issue, Takahashi *et al.* (1) show that experiencing envy at another person's success activates

pain-related neural circuitry, whereas experiencing schadenfreude—delight at someone else's misfortune—activates reward-related neural circuitry.

Neuroscientists have identified neural systems responsible for experiences of pain and pleasure. The cortical pain network consists primarily of the dorsal anterior cingulate cortex (dACC), insula, and somatosensory cortex, with subcortical contributions from the periaqueductal gray and thalamus (2) (see the figure). Whereas the somatosensory cortex is associated with sensory aspects of cutaneous physical pain (e.g., its location on the body), the dACC is associated with the distressing aspect of pain.

The brain's reward circuitry (see the figure) consists of neural structures receiving the neurotransmitter dopamine from the ventral

Analyses of brain activity reveal a link between social and physical pains and pleasures.

tegmental area, and responds to physically rewarding stimuli such as food, drugs, and sexual activity. The nucleus accumbens in ventral striatum plays a critical role in reward learning and pleasurable states, while the ventromedial prefrontal cortex and amygdala are also major dopaminergic targets that have been implicated in reward processes (3).

Although it is expected that these networks produce robust responses to physical pains and pleasures, it is surprising that social pains and pleasures activate these same networks. For example, being socially excluded activates the dACC and insula, with the dACC showing greater activity to the extent that an individual feels greater social pain (4). Grieving over the death of a loved one and being treated unfairly also activate these regions (5, 6). Alternatively, social rewards

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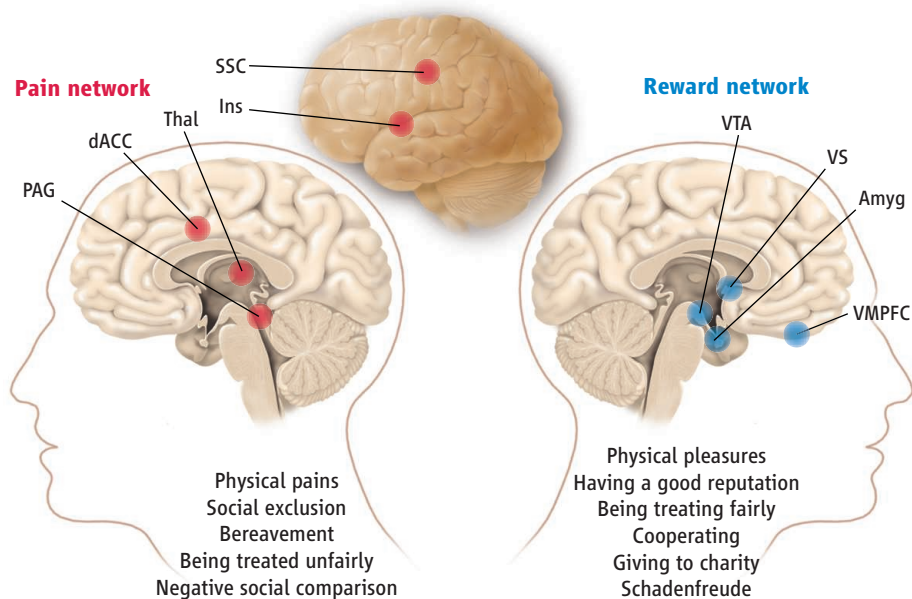
activate the same reward network as desirable foods and drinks. Having a good reputation, being treated fairly, and being cooperative all activate the ventral striatum (7–9). Strikingly, making charitable donations activates the reward network more than receiving the same sum of money for oneself (10).

Although most would describe being excluded as painful and giving to charity as pleasurable, the connotations of these descriptions change as we learn that these experiences activate the same brain regions that respond to physical pains and pleasures. Such findings suggest that the brain may treat abstract social experiences and concrete physical experiences as more similar than is generally assumed.

These overlaps suggest that certain social psychological concerns may have the same motivational importance as other physical survival needs. For every state of deprivation associated with a particular need, there is a pain. Lack of food begets hunger, lack of water begets thirst, and lack of shelter begets thermal discomfort. Each of these pains motivates us to seek out the salve that will take the pain away and satisfy the underlying need. The process of satisfying such needs is pleasurable and rewarding. All basic survival needs share these dynamics between need deprivation and pain and between need satiation and pleasure. Moreover, for physical survival needs, the greater the deprivation and attendant pain, the more pleasurable it is to satisfy the need (e.g., food tastes better on an empty stomach).

Takahashi *et al.* demonstrate, for the first time, this dynamic interplay between social pains and pleasures. If maintaining one's social value is a need like other physical needs, then the greater the pain caused by negative social comparisons, the greater the pleasure in response to seeing the comparison target socially devalued (schadenfreude). The authors found that greater envy and dACC activity in response to a negative social comparison was associated with greater schadenfreude and ventral striatum activity when learning of that comparison target's subsequent downfall.

Given that physical needs intuitively seem more critical to survival than social needs, why would the brain have evolved to treat them as motivationally similar? It is clear why food and water are needed and why their deprivation causes pain. But why use the neural system for physical pain to deal with social pains? One critical determinant may be the dependence of mammalian newborns on others for survival. Because newborn mammals are relatively immature—incapable of securing food, water, and shelter for themselves—



The pain and pleasure systems. The pain network consists of the dorsal anterior cingulate cortex (dACC), insula (Ins), somatosensory cortex (SSC), thalamus (Thal), and periaqueductal gray (PAG). This network is implicated in physical and social pain processes. The reward or pleasure network consists of the ventral tegmental area (VTA), ventral striatum (VS), ventromedial prefrontal cortex (VMPFC), and the amygdala (Amyg). This network is implicated in physical and social rewards.

they and the survival of their species depend on an ongoing bond between caregiver and infant (11). For both caregiver and infant to feel pain upon separation ensures social connection and thus offspring survival. In a sense, for mammalian infants, social needs take precedence over physical needs because meeting the social needs is what allows the physical needs to be met as well.

In addition to the caregiver-infant bond, connections to a social group also promote survival. When responsibility for food acquisition, protection from predators, and care for offspring are distributed among group members (rather than being the sole responsibility of a single individual), individual group members are more likely to survive (12). Being fair, cooperative, or charitable may increase the survival of the group and thus one's own offspring. Moreover, group members who are not cooperative are more likely to be ostracized, which greatly lowers chances of survival (13). Thus, evolutionary pressures may have created internal mechanisms that register being socially cooperative as pleasurable and being ostracized as painful in order to promote the maintenance of group bonds and ensure survival.

The link between social and physical pains and pleasures adds to the growing chorus of neurocognitive findings that point to the critical importance of the social world for the surviving and thriving of humans. It seems non-

coincidental that the size of the prefrontal cortex correlates with the size of social groups across primate species (14), that there is a dedicated neurocognitive network for social cognition that is preferentially activated when the mind is at rest (15), and that social and physical needs rely on shared neural substrates. Our attentiveness to the social world may sometimes seem like a diversion from more concrete concerns, but increasingly, neuroscience is revealing ways in which such attention is actually an adaptive response to some of our most vital concerns.

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