behavioural choice. The reward dopamine neurons indirectly impair the function of the punishment dopamine neurons, and this drives unconstrained reward seeking (Fig. 1). These data resolve how the processing of signals that drive opposing behaviours influences future decisions about risk, and add a fundamental principle through which reward is assessed and drives motivated behaviour.

This work was possible because subpopulations of dopamine neurons within a heterogeneous dopamine reward system could be identified and manipulated, and combining this with approaches that map neural connections showed that these subpopulations receive diverse and highly parallel inputs. The authors' findings reveal the complexity of reward encoding and the role of functionally interconnected brain compartments in representing multiple reward types that are gated by a variety of motivational states, including thirst and hunger. Future studies might address how long aberrant behavioural choices persist, and whether these mechanisms occur in the face of more intense rewards, such as intoxicating substances.

Given that there are strong parallels between the reward circuitry of fruit flies and that of mammals[15], Jovanoski and colleagues' work provides a fundamental framework for understanding how animals remember rewards and overcome aversive stimuli to seek them. One caveat is that the study uses data averaged from groups of fruit flies, and is therefore not able to address recurrent or compulsive reward-seeking behaviour, which would need to be examined in individual animals. However, a similar internal-state-gated network of opposing dopamine neurons could explain how unconstrained reward seeking occurs in addiction. Further investigation of this network could improve our understanding of depression, addiction and other mental-health disorders in which the balance between risk and reward is disrupted.

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Condensed-matter physics

Flat bands taken to another dimension

Xingjiang Zhou

Experiments reveal flat bands in the relationship between the energy and the momentum of electrons in a 3D solid. Such behaviour is indicative of unusual physical phenomena, and has previously been seen only in 2D materials. **See p.301**

The material properties of a crystalline solid are dictated by how electrons move between its atoms. For example, electrons in an insulator are fixed in place, whereas metals have electrons that are free to roam. The electrons' motion is, in turn, determined by the ranges of energies that they can and cannot have in the solid, which manifest as bands in the relationship between energy and momentum. These bands are 'flat' when the energy of the electrons does not change with momentum[1,2]. Such states have been predicted and observed in some systems, but only in materials that are effectively 2D. On page 301, Wakefield *et al.*[3] report flat bands in a 3D material, which could reveal behaviours that are even more fascinating than those seen in 2D.

The basis of electronic band structure is the fact that electrons move around the atomic nucleus in orbitals, which have discrete energy levels. When atoms come together to form a solid, electrons can hop from one atom to another, causing these energy levels to split — and form bands. Electrons in solids first occupy the lowest-energy band, and then successively fill higher-energy bands. The occupancy of the highest-energy band that contains electrons determines the properties of the material. If this band is partially filled, electrons can move around and the material is a metal. If the band is fully filled, electrons are fixed and it is a semiconductor or an insulator.

The relationship between the energy and the momentum of electrons in a crystalline solid also controls their velocity and effective mass (the ratio between an electron's mass in the solid and its true mass). The presence of a flat band means that there are many electrons with a similar energy, zero velocity and an infinitely large effective mass. These three factors have the effect of enhancing correlations between the electrons, which can lead to technologically useful states, such as ferromagnetism (the type of magnetism found in iron)[4] and superconductivity[5] (zero electrical resistance). Flat bands can give rise to even more exotic behaviours[6–10]. The question, therefore, is how can a flat band be induced in a material?

In 1991, some specific lattice configurations were predicted to be able to host flat bands[4]. One such configuration is the kagome lattice, a network of corner-sharing triangles that can, in theory, produce a perfectly flat band (Fig. 1a). In this lattice, electrons still hop from each site to their nearest neighbour, but because of the lattice geometry, the electrons are localized within a hexagon and cannot move from one hexagon to the next. The flat band that forms is 'topological' in nature, which means that its electronic structure cannot be deformed without changing the fundamental nature of the material[11].

The prediction of this perfectly flat band has been verified in several 2D kagome materials[12–14] using a technique called angle-resolved photoemission spectroscopy (ARPES), which maps out the electronic band structure of a system directly[15]. The flat band is present only in the plane of the material; it does not usually exist along the direction perpendicular to the plane. But theoretically, it is possible for a flat band to exist in a 3D network. Specifically, flat bands have been predicted to appear in all three spatial directions of a pyrochlore crystal structure, which comprises corner-sharing tetrahedra[16] (Fig. 1b). Experimental evidence of this state had, however, been missing — until now.

Wakefield *et al.* identified an alloy of calcium

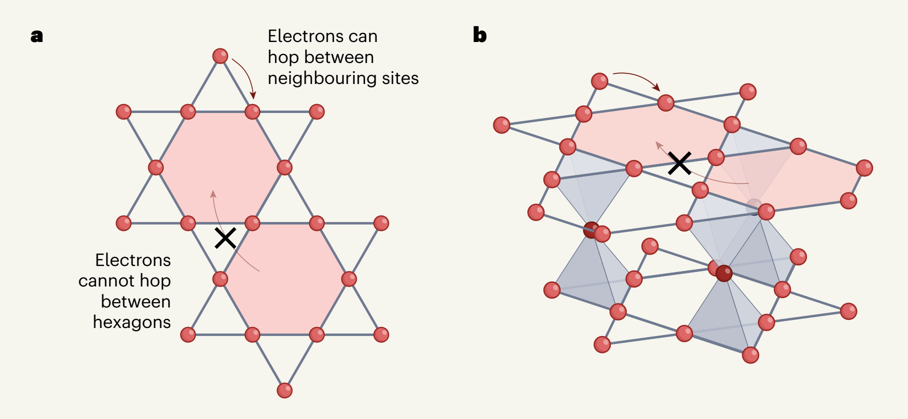

Figure 1 | Crystal lattices hosting flat bands. Electrons occupy orbitals with discrete energy levels, but, in solids, they can hop between atoms, causing these energy levels to form bands. If the bands are flat, the energies of the electrons do not change with their momenta, and this can lead to unusual physical phenomena. **a**, The 2D kagome lattice comprises corner-sharing triangles and hosts flat bands because electrons can hop between neighbouring sites, but are localized in each hexagon and cannot move from one hexagon to the next. **b**, Wakefield *et al.*[3] showed that flat bands also arise in a 3D solid containing a structure known as a pyrochlore lattice, raising hopes of finding more 3D flat-band materials.

and nickel ($CaNi_2$) as the right material for the job, because the nickel in this metal forms a pyrochlore lattice, as required by theory. They then used ARPES to probe the 3D electronic structure of $CaNi_2$, and observed flat bands extending along all three directions of the crystal lattice. These bands are not as flat as theory would suggest, partly because they mix with other bands, and also as a result of complications arising from the calcium atoms in $CaNi_2$. However, the authors' results represent a huge step forward in the effort to find 3D flat-band materials.

Flat bands produce exotic behaviours only when they lie close to the Fermi level, which is the highest energy level that is occupied by electrons. Wakefield and colleagues showed that the energy position of the flat bands can be tuned, by adjusting the chemical composition of another material with a pyrochlore lattice, $Ca(Rh_{1-x}Ru_x)_2$, which contains rhodium (Rh) and ruthenium (Ru) along with calcium. They were able to engineer the $Ca(Rh_{1-x}Ru_x)_2$ so that the flat band was very close to the Fermi level, and this enhanced the correlations between electrons, leading to the appearance of superconductivity with a relatively high critical temperature of 6.2 kelvin.

The effect of a flat band is expected to be more pronounced in 3D materials than it is in 2D materials. Flat bands combine strong electron correlations with topological behaviour, both of which are conducive to the formation of unusual phases. And certain phenomena and states of matter can be realized only in flat-band systems that have high dimensions[16,17].

Wakefield and colleagues' discovery of 3D flat bands has therefore created a new platform for studying these intriguing behaviours. It opens a path for finding other materials with 3D flat bands, and for investigating the exotic states that they are expected to host. The authors' demonstration that such bands can be engineered with chemical (and perhaps mechanical) tuning will have an important role in all these endeavours.

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Tumour biology

Cancer hijacks neuronal learning mechanisms

Matthew B. Dalva

Synaptic connections between cancer cells and neurons can boost tumour growth. Analyses of brain tumours reveal how cancer cells enhance the strength of synapses with neurons to promote tumour survival. **See p.366**

Cancer often results from the dysregulation of normal cellular mechanisms, because tumour cells can co-opt such processes to increase their own survival, proliferation and invasiveness. A great deal of effort has been made to develop therapies that target these processes, with the goal of slowing the growth of the tumour cells, reducing their proliferation or killing them. However, many cancers – particularly those of the brain – have not been successfully targeted by this approach, which suggests that other factors are involved in mediating cancer progression. On page 366, Taylor *et al.*[1] reveal that brain cancer harnesses an unexpected type of cellular process.

One mechanism that seems to increase the survival and invasiveness of tumour cells is their communication with the surrounding cellular environment[2,3]. These interactions have a central role in determining cancer progression and prognosis, and could therefore be a powerful therapeutic target. Taylor and colleagues show that brain tumours called gliomas and glioblastomas can hijack mechanisms that are normally associated with neuronal connections called synapses (Fig. 1).

The tumours take advantage of a process known as the adaptive neuronal plasticity of synapses, in which the strength of the connections between neurons can be increased or decreased in response to stimuli. These changes in synaptic strength often occur at excitatory synapses, at which the neurotransmitter glutamate is released. Adaptive increases in synaptic strength are thought to mediate the encoding, storage and retrieval of information, thus forming the basis of memories and learned behaviours. By targeting the