ing of spheres that still keeps the particles jammed in place. However, this form of packing is somewhat controversial (*6, 9*). Is this a meaningful number, or is it a function of exactly how the particles were arranged?

Although the question of packing of spheres has been of vital interest and importance, most real objects that we want to pack are not spheres, but are more irregular in shape. However, it has long been assumed, as physicists are wont to do, that what happens for spheres is immediately applicable to more complex shapes. It is, therefore, a great surprise that this is not the case at all. The new results are based on a very important question: If you use M&M's (a most ubiquitous object in some corners of the Princeton Physics Department where this work was done), how many candies can you pack into a large barrel? The result found by Donev *et al.* is surprising: The maximum volume fraction, while still keeping the candies completely disordered, is closer to $\varphi \approx 0.72$, much larger than it is for spheres. There are many more candies in that barrel than you thought.

Donev *et al.* do indeed use M&M candies, but of course, only the plain chocolate variety. They show that M&M's are nearly perfectly monodisperse ellipsoids. Repeated experiments, with different-sized ellipsoidal M&M's, give the same large number for the volume fraction. These experiments inspired a careful numerical investigation, in which the shape of the ellipsoids is systematically varied. The results suggest that, in fact, the more general value for the largest packing of irregular objects is actually about $\varphi \approx 0.74$. Spheres actually seem to be an anomaly, with the maximum volume fraction for random close packing dropping surprisingly sharply as the shape approaches that of a sphere.

The reason for this anomaly is not yet fully understood, but may well go back to the case of the still-disputed random loose packing. It has to do with the fact that the particles must be jammed in place, and must be in what is called static equilibrium (see the figure). That is, each particle has several nearest neighbors that touch it, and therefore exert a force on it. However, because each particle is perfectly stationary, or jammed in place, the sum of all the forces on it must be identically zero. Thus, there must be no net force to cause the particle to move, and no net torque to cause the particle to rotate. For a perfectly symmetric object, such as a sphere, the forces exerted by the neighboring particles can only cause it to translate; they cannot cause it to rotate; thus there can be no torque on a sphere. By contrast, for an ellipsoid, the forces exerted by the neighbors can cause both a translation and a rotation. As a result, to ensure that all the forces sum to zero for an arbitrary orientation of neighbors, several more neighbors are required, on average, for the ellipsoidal M&M's than for the spherical marbles. This in turn requires the higher volume fraction observed.

This higher volume fraction has many important consequences. It explains how to pack objects into a smaller volume, which is important for storage and shipping. The key is to ensure that the particles are not spherical. It also suggests ways to achieve a higher volume fraction of particles for making things such as building structures or ceramics. However, perhaps most important, it explains why eating M&M's for lunch one by one always takes longer than eating a bag of spherical candies of the same total volume. This is, of course, crucial information when you are dieting and M&M's are the only food you eat all day.

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NEUROSCIENCE

Conflict and Cognitive Control

Kenji Matsumoto and Keiji Tanaka

Cognitive control is necessary when we block a habitual behavior and instead execute a less-familiar behavior. Because cognitive control requires an effort, it is not efficient to maintain a high level of control all the time—the nervous system needs to know when cognitive control is necessary. On page 1023 of this issue, Kerns *et al.* (*1*) investigate the brain mechanisms that underlie the recruitment of cognitive control.

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Two cortical areas in the frontal part of the brain, the anterior cingulate cortex (ACC) and the lateral prefrontal cortex (LPFC), are considered essential for recruiting cognitive control. This conclusion is based both on the psychological examination of brain-damaged patients and on the imaging of normal human subjects (*2*). Botvinick and colleagues have proposed that the ACC detects conflicts between plans of action, and in response to these conflicts recruits greater cognitive control in the LPFC (*3*). This hypothesis is consistent with evidence showing the involvement of the LPFC in the execution of cognitive control, such as selective attention and response inhibition (*4*). Activation of the ACC by action-plan conflicts has also been reported (*5–7*). However, as yet there is no direct evidence of a connection between the detection of conflicts in the ACC and the subsequent greater control recruited in the LPFC.

The Stroop test is a useful tool for examining this connection. In this test, words denoting colors (such as red or green) are presented to human subjects in a variety of different colors, one at a time. The subject is instructed to report the physical color in which the word is presented (the color-naming condition) or the color that the word denotes (the word-reading condition). Subjects find it difficult to respond correctly in the color-naming condition when the physical color of the presented word is different from its meaning (incongruent). This difficulty is apparent not only in the subject's frequency of erroneous responses but also in the subject's reaction time for correct responses. The reaction time tends to be longer in incongruent trials than in congruent trials (where the physical color matches the meaning). Because human subjects are well trained to read words, a motor plan for reading the presented word is spontaneously initiated, contrary to the instruction to report the color in which the word is presented. This results in a conflict between two plans of response actions, which in turn increases the reaction time (see the figure, left). Functional magnetic resonance imaging (fMRI) has revealed greater activation in the ACC during incongruent versus congruent trials (*6*).

When an incongruent trial is followed by another incongruent trial, it is expected that a conflict detected in the first trial recruits greater cognitive control in the second trial. Thus, there should be stronger

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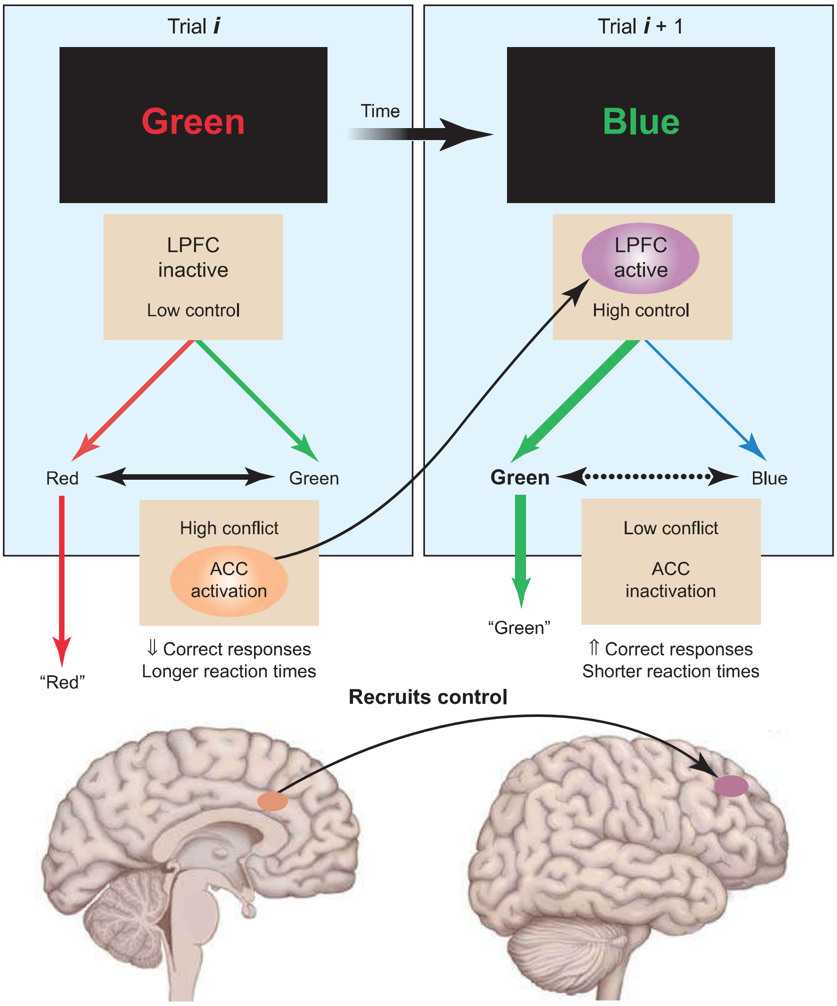

Recruiting cognitive control. Using fMRI, Kerns *et al.* (*1*) examined activation of the ACC and LPFC in consecutive trials of the Stroop test in human subjects. **(Left)** When the word presented to subjects is in a different color from the color the word denotes—an incongruent trial (*i*)—the resulting conflict regarding which action plan to execute induces an increase in ACC activity. **(Right)** When the first incongruent trial is followed by a second incongruent trial (*i* + 1), there is increased activity in the LPFC due to recruitment of cognitive control during the first trial, resulting in a shorter reaction time for the test response. The authors propose that detection of conflicts between plans of action by the ACC leads to recruitment of cognitive control in the LPFC.

control in incongruent trials that follow an incongruent trial compared with incongruent trials that follow a congruent trial (see the figure, right). This expectation has been confirmed by comparing the reaction times in the two types of incongruent trials. However, neural correlates of this sequence, that is, detecting conflicts in one trial and greater cognitive control in the next trial, have not been shown. By using event-related fMRI, Kerns *et al.* now report correlations between ACC activity, LPFC activity, and reaction time in subjects performing the Stroop color-naming task. Specifically, these authors found that ACC activity in an incongruent trial had a positive correlation with LPFC activity in the next trial. They also found that ACC activity in an incongruent trial had a negative correlation with the reaction time of the subject in the following incongruent trial. These findings should garner more support for the proposal that the ACC recruits control in the LPFC based on conflict monitoring.

Kerns *et al.* (*1*) propose that the ACC strengthens the cognitive control recruited by the LPFC, and that the ACC does not specify the manner or direction of control. Their previous studies showed that the ACC was not activated when the subject strengthened attention to the relevant sensory dimension (physical color in the color-naming condition) before a sample word was presented in the trial (*6*). However, subjects succeeded in responding correctly in most incongruent trials, although the reaction times were longer, indicating that the conflicts were somehow resolved within the trial. The ACC may contribute to this "consequential" control enabling selection of one of the two action plans evoked by the word presentation.

The cingulate motor area of the ACC has direct projections to the primary motor cortex. The remaining parts of the ACC have indirect projections to the primary motor cortex via the cingulate motor area and other medial higher motor areas (*8*). Moreover, recent single-cell recording studies in monkeys suggest mechanisms by which the ACC resolves conflicts between action plans. When monkeys select one of two actions based on anticipation of the goal (reward type) and recent experience of the contingency between action and goal, the neuronal activity representing the anticipated goal occurs first. Then neuronal activity representing a combination of the anticipated goal and intended action occurs after a short delay in the ACC (*9*). The former neuronal activity might trigger the latter, and this sequence of activities might underlie goal-based action selection. Neuronal activities in the ACC that are specific for the selection of particular actions have also been found in other studies (*10*, *11*). Sensory cues may evoke multiple action plans, one of which is selected by the ACC according to such values as the anticipated goal and whether the action is justified.

Cognitive control recruited by the ACC may be "consequential," that is, based on conflicts between evoked plans of concrete actions. In contrast, in the LPFC, control may be "preemptive," that is, capable of preventing future conflicts, and may occur at a more strategic level, for example, by increasing attention to the task-related aspects of sensory stimuli. Because neurons selective for different actions are interspersed in local regions, the limited spatial resolution of fMRI might have obscured these action-specific activities in the ACC in previous fMRI studies. Future studies in monkeys and humans should elucidate further the mechanisms defining consequential and preemptive cognitive control and the parts played by the ACC and LPFC.

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