BEHAVIORAL SCIENCE

GOOD HABITS, BAD HABITS

Researchers are pinpointing the brain circuits that can help us form good habits and break bad ones

By Ann M. Graybiel and Kyle S. Smith

IN BRIEF

As we repeat a behavior, it becomes laid down in special habit circuits involving the brain's striatum. The circuits treat the habit as a single "chunk," or unit, of automatic activity.

Another brain region, the neocortex, monitors the habit, however. Tweaking the neocortex in laboratory rats with light signals can interrupt a habit and even prevent one from forming.

By learning more about how these brain structures operate, researchers could find drugs, behavioral therapies and simple tricks to help us control habits, good and bad.

Illustration by Marek Haiduk

Ann M. Graybiel is an Institute Professor at the Massachusetts Institute of Technology and an investigator at the McGovern Institute for Brain Research at M.I.T.

Kyle S. Smith is an assistant professor of psychological and brain sciences at Dartmouth College.

EVERY DAY WE ALL ENGAGE IN A SURPRISING NUMBER OF HABITUAL BEHAVIORS. MANY OF THEM, FRO brushing our teeth to driving a familiar route, simply allow us to do certain things on autopilo so that our brains are not overtaxed by concentrating on each brushstroke and countless tin adjustments of the steering wheel. Other habits, such as jogging, may help keep us health Regularly popping treats from the candy dish may not. And habits that wander into the territory of compulsions or addictions, such as overeating or smoking, can threaten our existence.

Even though habits are a big part of our lives, scientists have had a hard time pinning down how the brain converts a new behavior into a routine. Without that knowledge, specialists have had difficulty helping people break bad habits, whether with medicines or other therapies.

New techniques are finally allowing neuroscientists to decipher the neural mechanisms that underlie our rituals, including defining our so-called habit circuits—the brain regions and connections responsible for creating and maintaining our routines. The insights from this work are helping neuroscientists to figure out how the brain builds good habits and why all of us seem to struggle with breaking habits that we do not particularly care for, as well as those we are told to stop by doctors or loved ones. The research suggests that by deliberately conditioning our brain, we might be able to control habits, good and bad. That promise springs from one of several surprises: that even when it seems we are acting automatically, part of our brain is dutifully monitoring our behavior.

WHAT IS A HABIT, REALLY?

HABITS SEEM TO STAND OUT as clear-cut actions, but neurologically, they fall along a continuum of human behavior.

At one end of that continuum are behaviors that can be done automatically enough to let us free up brain space for different pursuits. Others can command a lot of our time and energy. Our habits emerge naturally as we explore our physical and social environments and our inner feelings. We try out behaviors in particular contexts, find which ones seem beneficial and not too costly, and then commit to those, forming our routines.

We all begin this process when we are very young. Yet it comes with a trade-off that can work against us. The more routine a behavior becomes, the less we are aware of it. We lose the fully alert surveillance of that behavior. Did I actually turn off the stove before I left the house? Did I lock the door? This loss of surveillance not only can interfere with our daily functioning, it also can allow bad habits to creep up on us. Many people who gain weight, just a couple of pounds at a time, suddenly reali that they have been going to the snack aisle or the doughn shop more and more frequently, scarcely thinking about it they do.

This insidious failure to check our actions also means th habits can become akin to addictions. Witness computer ga ing, Internet gambling, and constant texting and tweeting—a of course alcohol and drug use. A repetitive, addiction-driv pattern of behavior can take over part of what had been delibe ate choice. Neuroscientists are still grappling with wheth addictions are like normal habits, only more so, although th certainly can be thought of as extreme examples at the oth end of the continuum. So can certain neuropsychiatric con tions such as obsessive-compulsive disorder—in which though or actions become all-consuming—and some forms of depre sion, in which negative thoughts may run in a continuous loo And extreme forms of habit may be involved in autism a schizophrenia, in which repetitive, overly focused behavic are a problem.

DELIBERATE BEHAVIOR BECOMES ROUTINE

ALTHOUGH HABITS FALL ALONG different parts of the behavi spectrum, they share certain core features. Once they form, example, they are stubborn. Tell yourself to "stop doing th and most of the time the lecture fails! Part of the reason may that this critique usually happens too late, after the behav plays out and its consequences are being felt.

This stubbornness, in particular, has been a clue to uncov ing the brain circuitry responsible for habit formation and ma tenance. Habits become so ingrained that we perform them ev when we do not want to, in part because of what are called "re forcement contingencies." Say you do A, and then you are warded somehow. But if you do B, then you are not rewarded are even punished. These consequences of our actions—the c tingencies—push our future behavior one way or another.

Signals discovered in the brain seem to correspond to this re forcement-related learning, as shown in studies originally conducted by Wolfram Schultz and Ranulfo Romo, both then at the University of Fribourg in Switzerland, and today modeled by computational scientists. Particularly important are "reward-prediction error signals," which, after the fact, indicate the mind's assessment of how accurate a prediction about a future reinforcement actually turned out to be. Somehow the brain computes these evaluations, which sculpt our expectations and add or subtract value from particular courses of action. By monitoring our actions internally and adding a positive or negative weight to them, the brain reinforces specific behaviors, shifting actions from deliberate to habitual—even when we know we should not gamble or overeat.

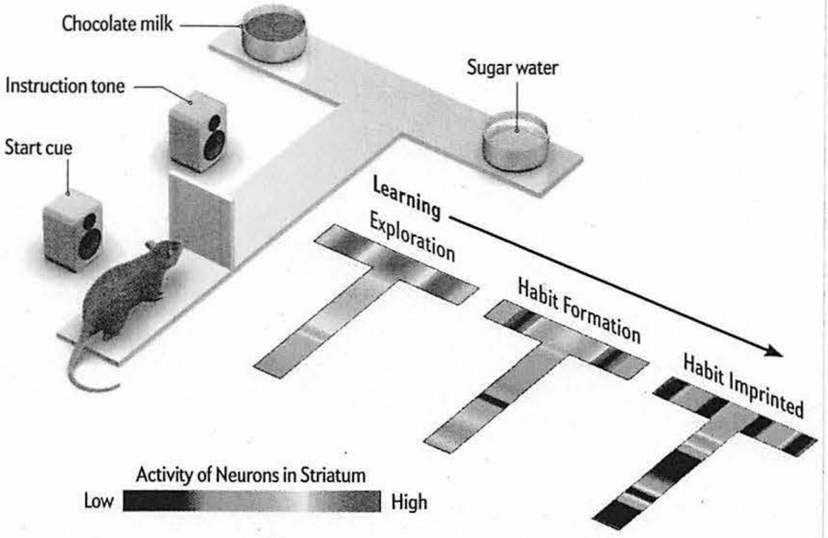
We and others wondered what goes on in the brain's wiring to cause this shift and whether we could interrupt it. In the Graybiel lab at the Massachusetts Institute of Technology, our group began experiments to decipher which brain pathways were involved and how their activity might change as habits formed.

First, we needed an experimental test for determining whether a behavior is a habit. British psychologist Anthony Dickinson had devised one in the 1980s that is still widely used. He and his colleagues taught lab rats in a test box to press a lever to receive a food treat as a reward.

THE EXPERIMENT

Acting without Thinking

Tests on rats revealed that the brain treats a habit as a single unit of behavior. The rats learned to run down a T-maze and turn left or right toward a reward, depending on an instruction sound. During early runs (*first colored T*), activity in the brain's striatum was high (*yellow* and *red*) most of the time. As a habit formed (*second T*), activity quieted (*green* and *blue*) except when the rat had to decide to turn or to drink. Once a habit set in (*third T*), activity was high only at the start and finish, marking one unit of behavior.



When the animals had learned this task well and were back in their cages, the experimenters "devalued" the reward, either by letting the rats eat the reward to the point of oversatiation or by giving them a drug that produced mild nausea after the reward was eaten. Later on, they brought the rats back to the experimental box and gave them the choice of pressing the lever or not. If a rat pressed the lever even though the reward was now sickening, Dickinson considered the behavior to be a habit. But if a rat was "mindful"—if we can speak of mindfulness in a rat—then it did not press the lever, as though it realized that the reward was now unpleasant; it had not formed a habit. The test gave scientists a way to monitor whether or not a shift from purposeful to habitual behavior had occurred.

IMPRINTING A HABIT ON THE BRAIN

BY USING VARIATIONS of this basic test, researchers, including Bernard Balleine of the University of Sydney and Simon Killcross of the University of New South Wales in Australia, have found clues suggesting that different brain circuits take the lead as deliberate actions become habitual. New evidence from experiments on rats, as well as on humans and monkeys, now points to multiple circuits that interconnect the neocortex—regarded as the crowning glory of our mammalian brain—and the striatum, at the center of the more primitive basal ganglia, which sit at the core of our brain [*see box on next page*]. These circuits become more or less engaged as we act deliberately or habitually.

We taught rats and mice to perform simple behaviors. In one task, they learned to run down a T-shaped maze once they heard a click. Depending on an audio "instruction" cue that then sounded as they ran, they would turn left or right toward the top of the T and run to that end to receive one kind of reward or another. Our goal was to understand how the brain judges the pros and cons of behaving in a particular way and then stamps a sequence of behavior as a "keeper"—a habit. Our rats certainly did develop habits! Even when a reward had become distasteful, the rats would run to it when the instruction tone sounded.

To figure out how the brain stamps a behavior as one to make a habit, the M.I.T. lab began recording the electrical activity of small collections of neurons (brain cells) in the striatum. What our group found surprised us. When the rats were first learning the maze, neurons in the motor-control part of the striatum were active the whole time the rats were running. But as their behavior became more habitual, neuronal activity began to pile up at the beginning and end of the runs and quieted down during most of the time in between. It was as though the entire behavior had become packaged, with the striatal cells noting the beginning and end of each run [*see box above*]. This was an unusual pattern; what seemed to be happening was that the striatal cells were malleable and could help package movements together while leaving relatively few "expert cells" to handle the details of the behavior.

COURTESY OF ANN M. GRAYBIEL (*heat maps*)

Illustrations by AXS Biomedical Animation Studio

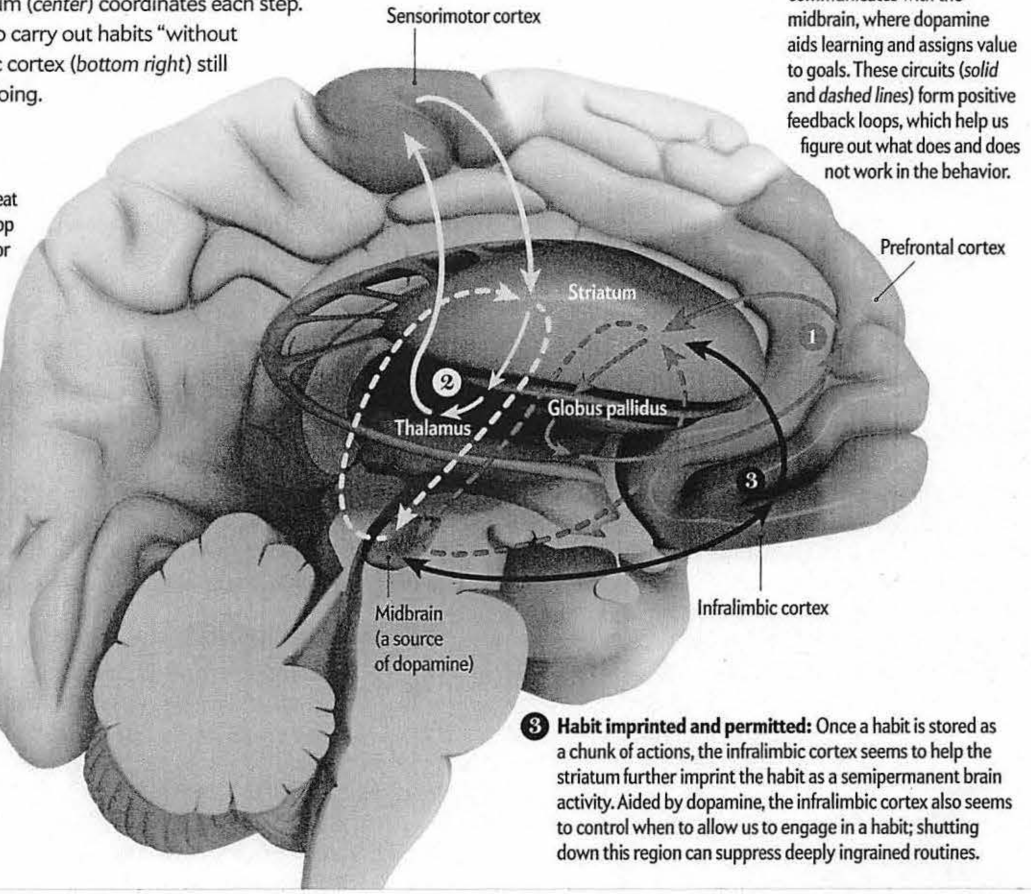
BRAIN ACTIVITY

How Habits Form

We use three steps to learn and lock in habits: explore a new behavior, form a habit, then imprint it into the brain (*colored numbers*). Although scientists have not refined all the details, the striatum (*center*) coordinates each step. Even though we seem to carry out habits "without thinking," the infralimbic cortex (*bottom right*) still monitors what we are doing.

① **New behavior explored:** The prefrontal cortex communicates with the striatum, and the striatum communicates with the midbrain, where dopamine aids learning and assigns value to goals. These circuits (*solid* and *dashed lines*) form positive feedback loops, which help us figure out what does and does not work in the behavior.

2 **Habit forms:** As we repeat a behavior, a feedback loop between the sensorimotor cortex and the striatum becomes strongly engaged, which helps us stamp routines into a single unit, or chunk, of brain activity. The chunk partly resides in the striatum and relies on dopamine input from the midbrain.



③ **Habit imprinted and permitted:** Once a habit is stored as a chunk of actions, the infralimbic cortex seems to help the striatum further imprint the habit as a semipermanent brain activity. Aided by dopamine, the infralimbic cortex also seems to control when to allow us to engage in a habit; shutting down this region can suppress deeply ingrained routines.

This pattern reminded us of the way the brain lays down memories. We all know how helpful it is to remember a string of numbers as larger units instead of one by one—such as thinking of a phone number as "555-1212" instead of "5-5-5-1-2-1-2." The late American psychologist George A. Miller coined the term "chunking" to refer to this packaging of items into a memory unit. The neural activity we observed at the beginning and end of a run seemed similar. It is as though the striatum sets up boundary markers for chunks of behavior—habits—that the internal evaluation process has decided should be stored. If true, this maneuver would mean that the striatum essentially helps us combine a sequence of actions into a single unit. You see the candy dish, and you automatically reach for it, take a treat and eat it "without thinking."

Researchers have also identified a "deliberation circuit," which involves another part of the striatum and is active when choices are not made on autopilot and instead require some decision making.

To understand the interplay between these deliberation and habit circuits, our group's Catherine Thorn recorded signals in both circuits simultaneously. As the animals learned a task, activity in the deliberation part of the striatum became strong during the middle of the runs, especially when the rats had to decide which way to turn at the top of the T, based on the instruction tone. This pattern was almost the exact opposite of the chunking pattern that we had seen in the habit striatum. And yet the activity did recede as the behavior became fully habitual. The pattern means that as we learn habits—at least as rats do—habit-related circuits gain strength, but changes in related circuits occur, too.

Because the striatum works together with a habit-related part of the neocortex at the front of the brain known as the infralimbic cortex, we then recorded activity in that region. This was an eye-opener as well. Even though we saw the beginning-and-end pile-up of activity in the habit striatum, during the initial learning period we saw very little change in the infralimbic cortex. It was not until the animals had been trained for a long time and the habit became fixed that the infralimbic activity changed. Strikingly, when it did, a chunking pattern then developed there, too. It was as though the infralimbic cortex was the wise one, waiting

SCIENTIFIC AMERICAN ONLINE For insight about whether obsession is a habit, see ScientificAmerican.com/jun2014/graybiel

until the striatal evaluation system had fully decided that the behavior was a keeper before committing the larger brain to it.

STOP THAT!

WE DECIDED TO TEST whether the infralimbic cortex has online control over whether a habit can be expressed by using a new technique called optogenetics. With this technique, we could place light-sensitive molecules in a tiny region of the brain, and then, by shining light on the region, we could turn the neurons in that region on or off. We experimented with turning off the infralimbic cortex in rats that had fully acquired the maze habit and had formed the chunking pattern. When we turned off the neocortex just for a few seconds while the rats were running, we totally blocked the habit.

The habit could be blocked rapidly, sometimes immediately, and the habit blockade endured even after the light was turned off. The rats did not stop running in the maze, however. It was just the habitual runs to the devalued reward that were gone. The animals still ran just fine to reach the good reward on the other side of the maze. In fact, as we repeated the test, the rats developed a new habit: running to the good-reward side of the maze no matter what cue they were given.

When we then inhibited the same tiny piece of infralimbic cortex, we blocked the new habit—and the old habit instantly reappeared. This return of the old habit happened in a matter of seconds and lasted for as many runs as we tested, without our having to turn off the infralimbic cortex again.

Many people know the feeling of having worked hard to break a habit only to have it come back, full-blown, after a stressful time or after one relapse. When Russian scientist Ivan Pavlov studied this phenomenon in dogs many years ago, he concluded that animals never forget deeply conditioned behaviors such as habits. The most they can do is suppress them. We are finding the same stubbornness of habits in our rats. Yet remarkably, we can toggle the habits on and off by manipulating a tiny part of the neocortex during the actual behavior. We do not know how far this control could reach. For example, if we taught the rats three different habits in a row, then blocked the third one, would the second habit appear? And if we then blocked the second one, would the first one appear?

A key question was whether we could prevent a habit from forming in the first place. We trained rats just enough to have them reach the correct end of the T but not enough for the behavior to settle in as a habit. We then continued the training, but during each run we used optogenetics to inhibit the infralimbic cortex. The rats continued running well in the maze, but they never acquired the habit, despite many days of overtraining that usually would have made the habit permanent. A group of control rats that underwent the same training without the optogenetic interruption did form the habits normally.

BREAKING BAD HABITS

OUR EXPERIMENTS OFFER some curious lessons. First, no wonder habits can be so difficult to break—they become laid down and marked as seemingly standardized chunks of neural activity, a process involving the work of multiple brain circuits.

Yet surprisingly, even though habits seem nearly automatic, they are actually under continual control by at least one part of the neocortex, and this region has to be online for the habit to be enacted. It is as though the habits are there, ready to be reeled off, if the neocortex determines that the circumstances are right. Even if we are not conscious of monitoring our habitual behaviors—after all, that is a large part of their value to us—we have circuits that actively keep track of them on a moment-to-moment basis. We may reach out for the candy dish without "thinking," but a surveillance system in the brain is at work, like a flight-monitoring system in an airliner.

So how close are we to helping people clinically? It will likely be a long time before anyone can flip a switch to zap away our pesky habits. The experimental methods that we and others are using cannot yet be translated directly to people. But neuroscience is changing at lightning speed, and those of us in the field are closing in on something truly important: the rules that habits work by. If we can fully understand how habits are made and broken, we can better understand our idiosyncratic behaviors and how to train them.

It is also possible that our expanding knowledge could even help people at the severe end of the habit spectrum, providing clues for how to treat obsessive-compulsive disorder, Tourette's syndrome, fear or post-traumatic stress disorder.

Drug treatments and other emerging therapies could possibly do the trick to help with such harmful habits. But we are also impressed by how the lessons we have learned from this brain research support behavioral therapy strategies, which are often suggested for helping us to establish healthy habits and weed out unhealthy ones. If you want to condition yourself to jog in the morning, then perhaps you should put out the running shoes the night before, where you cannot miss them when you wake up next day. This visual cue mimics the audio cue we used to train the rats—and it could be especially effective if you reward yourself after the jog. Do this on enough mornings, and your brain might develop the chunking pattern that you want. Alternatively, if you want to forgo the candy dish, you could remove it from the living room or office—eliminating the cue.

Changing habits might never be easy. As Mark Twain said, "Habit is habit, and not to be flung out the window by any man, but coaxed downstairs one step at a time." Our experiments, however, lead us to an optimistic point of view: by learning more about how our brains establish and maintain routines, we hope we can figure out how people can coax themselves out of undesirable habits and into the ones they want.

MORE TO EXPLORE

Habits, Rituals, and the Evaluative Brain. Ann M. Graybiel in *Annual Review of Neuroscience*, Vol. 31, pages 359–387; July 2008.

Human and Rodent Homologies in Action Control: Corticostriatal Determinants of Goal-Directed and Habitual Action. Bernard W. Balleine and John P. O'Doherty in *Neuropsychopharmacology*, Vol. 35, pages 48–69; 2010.

Optogenetic Stimulation of Lateral Orbitofronto-Striatal Pathway Suppresses Compulsive Behaviors. Eric Burguière et al. in *Science*, Vol. 340, pages 1243–1246; June 7, 2013.

A Dual Operator View of Habitual Behavior Reflecting Cortical and Striatal Dynamics. Kyle S. Smith and Ann M. Graybiel in *Neuron*, Vol. 79, No. 2, pages 361–374; July 24, 2013.

FROM OUR ARCHIVES

Controlling the Brain with Light. Karl Deisseroth; November 2010.

The Joyful Mind. Morten L. Kringelbach and Kent C. Berridge; August 2012.

scientificamerican.com/magazine/sa