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Toolmaking shaped how our minds think today

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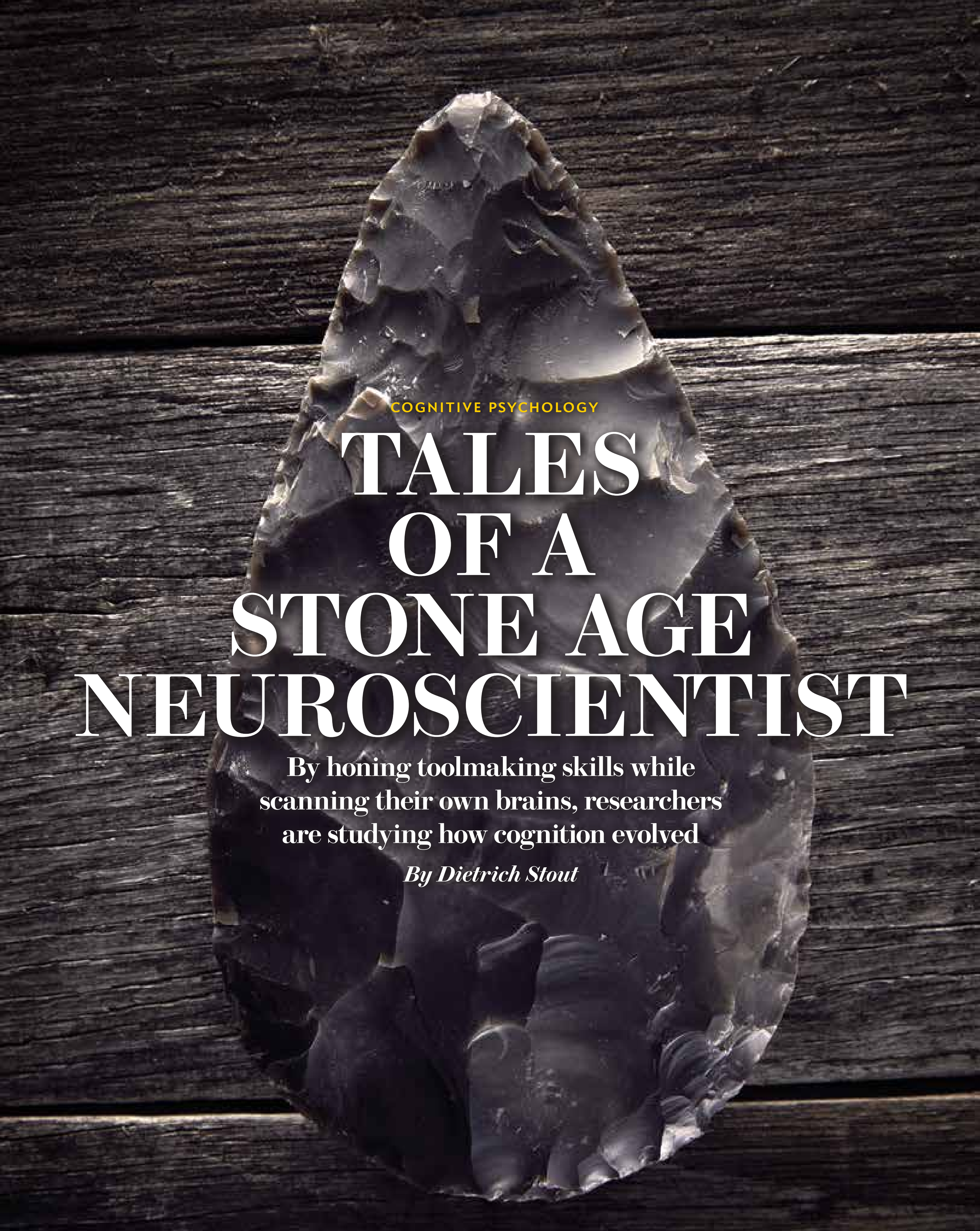
TOOLMAKER: Anthropology professor Dietrich Stout works on a stone tool at Emory University's Paleolithic Technology Laboratory.



COGNITIVE PSYCHOLOGY

TALES OF A STONE AGE NEUROSCIENTIST

By honing toolmaking skills while scanning their own brains, researchers are studying how cognition evolved

By Dietrich Stout

Photographs by Gregory Miller

Dietrich Stout is a professor of anthropology at Emory University. His research focus on Paleolithic stone toolmaking integrates experimental methods from diverse disciplines, ranging from archaeology to brain imaging.

I STILL HAVE THE FIRST STONE HAND AX I EVER MADE. IT'S A PRETTY POOR SPECIMEN, crudely chipped from a piece of frost-fractured flint I picked up on a walk through a farmer's field in West Sussex, England. It would not have impressed the human ancestors known to us as *Homo heidelbergensis*. These cousins of *Homo sapiens* from 500,000 years ago left much nicer hand axes at a nearby archaeological site in Boxgrove.

Still, I worked hard at making this simple cutting tool, and I am proud of it. What really matters, though, is not that I am dabbling in a new hobby. What matters is that my dabbling was intended to probe key questions of human evolution and the emergence of language and culture that are hallmarks of our species.

Replicating the skills of prehistoric peoples to understand human origins is not unprecedented—archaeologists have done it for decades. In the past 15 years, however, we have taken this approach in exciting new directions.

Working together, archaeologists and neuroscientists have brought brain-scanning machines to bear in observing what happens underneath the skull when a modern-day toolmaker chips away patiently at a stone, shaping it into a hand ax. With this view into the brain, we hope to identify which regions within may have evolved to help Paleolithic peoples chisel a well-crafted ax or knife from a formless hunk of rock.

These collaborations between archaeologists and neuroscientists have revived a largely discredited idea: that toolmaking was an important driver of the evolution of humans. British anthropologist Kenneth Oakley asserted 70 years ago in his influential book *Man the Tool-maker* that toolmaking was the "chief biological characteristic" of humanity that drove the evolution of our "powers of mental and bodily co-ordination."

The idea fell out of favor as behavioral scientists documented tool use and even toolmaking in nonhuman species such as apes, crows, dolphins and octopi. As paleontologist Louis Leakey put it in his now famous reply in 1960 to Jane Goodall's historic first report of chimpanzee tool use: "Now we must redefine tool, redefine Man, or accept chimpanzees as humans." For many scientists, complex social relationships replaced toolmaking as the central factor in primate brain evolution. In the 1980s and 1990s influential "Machiavellian intelligence" and "social brain" hypotheses argued that the greatest mental challenges primates face are in outsmarting other members of their own species, not in mastering their physical environment. These hypotheses gained empirical support from the observation that primate species that form large social groups also tend to have large brain sizes.

But more recent work, including our own, has shown that the "Man the Tool-maker" idea is not dead (although Oakley's language is clearly outdated). Toolmaking need not be unique to humans to have been important in our evolution. What matters is the kind of tools we make and how we learn to make them. Among primates, humans truly stand out in their ability to learn from one another. They are particularly adept at imitating what another person does. Mimicry is a prerequisite for learning complex technical skills and is thought to underlie the stunning ability of human culture to accumulate knowledge in a way that other apes do not. So it seems premature to abandon the idea that ancient stone tools might provide important information about human cognitive evolution. Teaching and learning increasingly complex toolmaking may even have posed a formidable enough challenge to our human ancestors that it spurred evolution of human language. In fact, many neuroscientists now believe that linguistic and manual skills both rely on some of the same brain structures.

To test these ideas, we have had to analyze carefully how an-

IN BRIEF

One way to answer questions about human evolution—and, in particular, the development of language and culture—entails replicating the skills used by prehistoric peoples.

A high-tech version of this approach uses brain-scanning machines to observe what neural regions become active when a toolmaker chips away at stone being shaped into a hand ax.

Crossover collaborations between archaeologists and neuroscientists have revived the largely discredited idea that the act of toolmaking served as a key driver of human evolution.

Teaching and learning the art of Stone Age toolmaking may, in fact, have posed a formidable enough challenge to our ancestors that it spurred the evolution of human language.

KNAPPING CLASS: Nada Khreisheh (*above, far right*) teaches hand-ax toolmaking 20 hours a week in the outdoor work area at Emory's Paleolithic Technology Laboratory. Each student receives a total of 100 hours of instruction. The flint hand ax (*right*) was the first such tool made by the author.

cient tools were made and compare these findings with evidence of the way relevant brain systems evolved. In studying these questions, we ran into immediate difficulties because neither brains nor behaviors appear in the fossil record. Given the paucity of evidence, our only recourse was to simulate in a laboratory setting the types of skills that were passed from generation to generation many millennia ago. For this reason, my students, collaborators and I have spent many years trying to emulate the skills of Paleolithic toolmakers.

EXPERIMENTAL ARCHAEOLOGY

USING MODERN BRAIN-SCANNING techniques to study some of humanity's oldest technologies may seem strange. We did get some funny looks when we first started wheeling carts of rocks into a state-of-the-art neuroimaging lab. But there is nothing startling about archaeologists performing experiments. Studying the present has long been one of the most important methods for understanding the past. Scientists have devised experiments to replicate ancient smelting techniques (archaeometallurgy) and to observe the relentless decay of animal carcasses (taphonomy) to better understand how they fossilize. Casual experiments in stone toolmaking—"knapping," as archaeologists call it—date back to the 19th century, and more controlled experiments are now well established in the study of lithic technology.

The scope of these experiments has grown in recent years. My graduate advisers—Nicholas Toth and Kathy Schick, both now at Indiana University Bloomington and the Stone Age Institute—proposed in 1990 using a then newly developed imaging technique to investigate what happens in the brain when making a Paleolithic tool. Following up on this initial idea during the past 15 years, I have made a major goal of my own research to figure out what happens inside the brain when a person knaps away at a piece of stone.

My lab now functions as something of an apprenticeship program in stone toolmaking. As I write, I can hear the tick, tick, tick of novice knappers adding yet more chips to a pile of broken flint in the work area outside my office at Emory University. Last year that pile reached 10 feet across, measured five inches in height and contained more than 3,000 pounds of shattered rock. I watch through a window as postdoctoral researcher Nada Khreisheh leans over to offer advice to a frustrated student.

Khreisheh currently spends about 20 hours a week training 20 students (each receives 100 hours of instruction) in the ancient art of hand-ax-making. This is our most ambitious project to date. Every training session is video-recorded so we are able to later analyze which learning techniques work best. We collect and measure each finished artifact to track skill development. The students must undergo repeated magnetic resonance imaging to examine changing brain structure and function, as well as psychological tests to see if particular abilities, such as planning or short-term memory, may be linked to toolmaking aptitude. It is a huge amount of work but essential to understanding the subtleties of this prehistoric technology.

The neophyte must master a percussive technology so demanding that a small error can compromise the entire workpiece.

If nothing else, all this effort has taught us that making these tools is difficult. But what we want to know is why it is so hard. Oakley and other proponents of the "Man the Tool-maker" argument thought the key to toolmaking was a "uniquely human" ability for abstract thought—that is, the ability to imagine different kinds of tools as a kind of mental template to be reproduced. I respectfully disagree. As any experienced craftsperson might tell you, knowing what you want to make is not the hard part. The difficulty lies in actually making it.

Knapping a hand ax requires the neophyte craftsperson to master a percussive technology that involves using a handheld "hammer" of stone, bone or antler to chip flakes off a stone, shaping it into a useful tool. The work requires powerful blows, accurate to within a few millimeters, which are delivered too rapidly to allow for a midswing correction. Like chiseling a marble sculpture, each strike removes something that cannot be put back. Even small errors can compromise the entire workpiece.

Using a motion-tracking system, movement scientist Blandine Bril and her colleagues at the School for Advanced Studies in the Social Sciences in Paris have shown that, unlike novices, experienced knappers adjust the force of their blows to produce flakes of different sizes. Stringing together a series of such blows to achieve an abstract design goal such as a hand ax is achievable only after acquiring the necessary control through long and painstaking practice.

Our ancestors faced the same challenges when they learned to make stone tools, and their lives probably depended on success in doing so. The demands of toolmaking—combined with complex social interactions for teaching these skills—may have become driving forces for human cognitive evolution. We have labeled this modern reboot of Oakley's "Man the Tool-maker" hypothesis as *Homo artifex*—the Latin word *artifex* signifying skill, creativity and craftsmanship.

TOOLS ON THE BRAIN

TEACHING STUDENTS to work stone is not the only technical challenge in learning about prehistoric practices. Standard brain imaging does not lend itself to certain aspects of studying stone toolmaking. If you have ever had a scan in a MRI machine, you probably remember being told emphatically not to move because it would ruin the image. Unfortunately, lying motionless inside a two-foot-wide tube is not conducive to knapping, although you might be tempted to nap.

In our early experiments, we circumvented this problem by using a brain-imaging technique known as FDG-PET (fluorodeoxyglucose positron-emission tomography). The intravenous line to supply the radioactive molecule used in PET to image brain activity needs to be injected into the foot to allow knappers to use their hands, a somewhat painful procedure. The test subject can then freely chip away at the chunk of stone destined to become an ax or knife while the tracer is taken up in metabolically active tissues in the brain. After the subject is finished, we run a scan to determine where in the brain the chemical has accumulated.

Using this technique, I set out to investigate two Stone Age technologies—Oldowan and Late Acheulean—that bracket the beginning and end of the Lower Paleolithic, a critical evolutionary period from 2.6 million to 200,000 years ago when the brains of hominins (humans and their extinct ancestors) nearly tripled in size. The question we wanted to explore in my lab was whether the development of these technologies placed new demands on the brain that, over the millennia, might have led through natural selection to its expansion.

Oldowan toolmaking (named after Tanzania's Olduvai Gorge, where it was first described in the mid-20th century by paleoanthropologist-archaeologist team Louis and Mary Leakey) involves striking sharp flakes from a cobble core. These simple flakes of rock became humanity's first "knives." Conceptually, toolmaking does not get much simpler. But our early PET data confirmed that the actual knapping process still remains a demanding task that goes far beyond just simply striking rocks together.

In our study, we allowed participants to practice for four hours without any instruction. As they became familiar with the task, they learned to identify and pay attention to particular features of the core, focusing, for instance, on areas that stuck out and would be easier to break. This learning is actually reflected in different patterns of activity in the visual cortex at the back of the brain before and after practice. But four hours' practice is not very long, even for humanity's earliest technology.

In truly experienced knappers, who can approximate the documented skills of real Oldowan toolmakers, something different is seen. As shown by Bril and her colleagues, experienced toolmakers distinguish themselves by their ability to control the amount of force applied during the percussive strike to detach flakes efficiently from the core. In the experts' brain, this skill spurred increased activity in the supramarginal gyrus in the parietal lobe, which is involved in awareness of the body's location in its spatial environment.

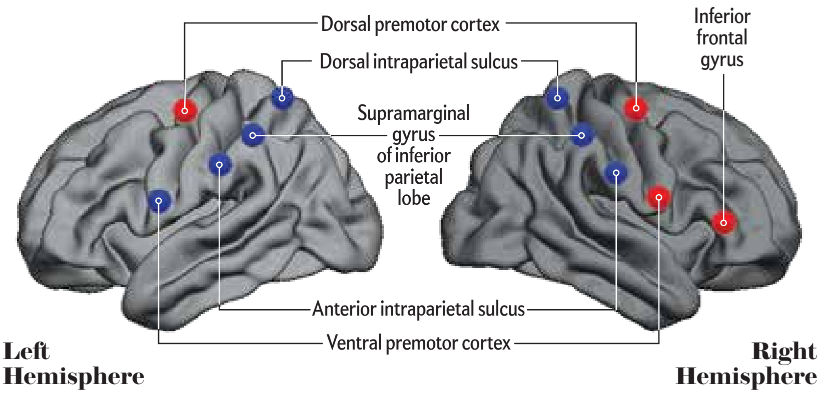
About 1.7 million years ago flake-based Oldowan technology began to be replaced by Acheulean technology (named after Saint-Acheul in France), which involved the making of more sophisticated tools, such as teardrop-shaped hand axes. Some Late Acheulean hand axes—those from the English site of Boxgrove that date back 500,000 years, for instance—were very finely shaped, with thin cross sections, three-dimensional symmetry and sharp, regular edges, all indicating a high level of knapping skill.

Modern knappers know that this technique requires not only precise control but carefully reasoned planning. Like a golfer selecting the right club, knappers use a variety of "hard" (stone) and "soft" (antler/bone) hammers as they work through planned flaking sequences that prepare core edges and surfaces to fracture in the desired pattern. They must switch back and forth between different subtasks while keeping the overall goal of a finished ax firmly in mind, resisting the temptation to take shortcuts. I know from bitter experience that you can't cheat the physics of stone fracture. It is better to just quit for the day when you are tired or frustrated.

IMAGING

An Expansion of Brainpower

Scanning techniques reveal how more of the brain gets used as toolmaking becomes more sophisticated. Imaging distinguished areas activated when a modern toolmaker crafted an implement reminiscent of simple Oldowan tools (2.6 million to 1.6 million years ago) compared with regions active when making Acheulean hand axes (1.6 million to 200,000 years ago). Blue dots denote brain regions utilized when chiseling both Oldowan and Acheulean tools; red ones lit up as well when knapping an Acheulean hand ax.



The demands of knapping a Late Acheulean tool also produce a characteristic signature in the brain scanner. Some of the same areas are involved in both Oldowan and Acheulean knapping. But our Acheulean PET data also show activation extending into a specific region of the prefrontal cortex, called the right inferior frontal gyrus. Decades of research by neuroscientists such as Adam Aron of the University of California, San Diego, have linked this region to the cognitive control needed to switch between different tasks and to hold back inappropriate responses.

We have since corroborated our PET results by using MRI, which provides higher-resolution imaging. To do this, we had to figure out a way to keep subjects immobilized. Working with social neuroscientist Thierry Chaminade, now at the Institute of Neurosciences of Timone at Aix-Marseille University in France, I asked subjects to lie still in the scanner and watch knapping videos rather than actually trying to make tools. This approach works because, as Chaminade and many others have shown, we use many of the same brain systems to understand observed actions as we do to execute them. Despite different methodologies, we found the same responses in the brain's visuomotor areas for both Oldowan and Acheulean knapping—and increased activity in the right inferior frontal gyrus when subjects watched the crafting of Late Acheulean tools.

We concluded that the ability to learn demanding physical skills would have been important to early Oldowan stages of human technological evolution but that Acheulean methods also required an enhanced level of cognitive control furnished by the prefrontal cortex. In fact, this observation agreed fairly well with the fossil evidence, which shows that some of the fastest increases in brain size over the past two million years occurred during the Late Acheulean. But that discovery did not establish which event was a cause and which was a consequence. Did toolmaking actually drive brain evolution in *H. artifex,* or did it simply come along for the ride? To address this question, we needed to get even more serious about studying how the brain learns to make tools.

LEARNING AND EVOLUTION

IT TOOK ME about 300 hours of practice to equal the skills of the Late Acheulean toolmakers at Boxgrove. The learning process might have gone quicker if I had worked with a teacher or been part of a toolmaking community. But I am not really certain. Despite decades of experimental knapping, almost no systematic studies of the learning process have been conducted. In 2008 Bruce Bradley, a professor of archaeology at the University of Exeter in England and a longtime experimental knapper, invited me to address that gap in our knowledge. Bradley wanted to train the next generation of British academic knappers, and he thought I might like to collect some neuroimaging data along the way to gain better insight into the learning process. He was right—I did.

One thing that I was particularly excited to try was a relatively new technique called diffusion tensor imaging (DTI), a form of MRI that allows scientists to map the white matter fiber tracts that serve as the brain's "wiring." In 2004 a group led by Bogdan Draganski, then at the University of Regensburg in Germany, used DTI to show structural changes in the brains of volunteers learning to juggle, which challenged the traditional view that the structure of adult brains is relatively fixed.

We suspected that learning to knap would also require some degree of neural rewiring. If so, we wanted to know which circuits were affected. If our idea was correct, we hoped to get a

COURTESY OF THIERRY CHAMINADE *Institute of Neurosciences of Timone, Aix-Marseille University*

CHIPS OFF THE BLOCK: A novice toolmaker knapped the finished flint hand ax, surrounded here by flakes detached while making the implement. Each piece is labeled, weighed and measured so that the process of learning motor and planning skills can be analyzed in detail.

glimpse of whether toolmaking can actually cause, on a small scale, the same type of anatomical changes in an individual that occurred over the course of human evolution.

The answer turned out to be a resounding yes: practice in knapping enhanced white matter tracts connecting the same frontal and parietal regions identified in our PET and MRI studies, including the right inferior frontal gyrus of the prefrontal cortex, a region critical for cognitive control. The extent of these changes could be predicted from the actual number of hours each subject spent practicing—the more someone practiced, the more their white matter changed.

Brain changes—what neuroscientists term “plasticity”—provide raw material for evolutionary change, an effect known as phenotypic accommodation. Plasticity allows species the flexibility to try out new behaviors—to “push the envelope” of their current adaptation. If they happen to discover a good trick, it enters their behavioral repertoire, and the evolutionary race is on: natural selection will favor any variations that enhance the ease, efficiency or reliability of learning the new trick. Our result thus provided important evidence that the idea of *H. artifex* was viable—and that toolmaking *could* actually have driven brain change through known evolutionary mechanisms.

With that information in hand, we needed to know next whether the anatomical responses we had observed paralleled specific evolutionary developments in the human brain. Fossil skulls cannot provide detailed information about changes to internal brain structures, so we turned to the next best thing: a direct comparison with one of our closest living relatives, the chimpanzee.

Fortunately, I had already enlisted the assistance of Erin Hecht, a recent Emory Ph.D., now at Georgia State University, to assist with the DTI analyses. Hecht’s dissertation work comparing chimpanzee and human neuroanatomy had given her access to precisely the data and expertise we needed. The result, published last year, was a DTI-based virtual dissection of white matter tracts in the two species that would identify any differences in the relevant brain circuits. It confirmed what we had suspected: the toolmaking circuits identified in our PET, MRI and DTI studies were indeed more extensive in humans than in chimps, especially when it came to connections to the right inferior frontal gyrus. This finding became the final link in a chain of inferences from ancient artifacts to behavior, cognition and brain evolution that I had been assembling since my days as a graduate student in the late 1990s. It provides powerful new support for the old idea that Paleolithic toolmaking helped to shape the modern mind. It is far from the end of the story, however.

THROUGH THE KEYHOLE

I LOVE STONE TOOLS, but they provide us with only the narrowest keyhole view of the complex lives of our ancestors. Like a geologist with a seismograph, the trick is to turn these bits of knowledge from the neuroscience of toolmaking into a rich model of Stone Age existence.

Although the evidence from stone tools is limited, we could have done worse. Stone toolmaking takes as much time to learn as many academic skills: a typical American college class is supposed to require about 150 hours of work (10 hours a week over a 15-week semester). In the study with Bradley, trainees logged an average of 167 hours' practice and were still struggling with Acheulean hand-ax-making by the end. Perhaps I should not feel too bad about the 300 hours it took me to learn. But sticking to such a tedious and frustrating practice regimen requires motivation and self-control, both intriguing attributes from an evolutionary perspective.

Motivation can come externally from a teacher or internally from the anticipation of a future reward. Many researchers have considered teaching to be the defining feature of human culture, whereas anticipating the future is clearly vital to everything from social relationships to technical problem solving.

Of course, motivational "carrots" take you only so far without the "stick" of self-control. The ability to exercise self-control—the inhibition of counterproductive impulses—is critical to many kinds of cognitive skills. In fact, a recent study led by Evan MacLean of Duke University found self-control and future planning to be correlated with larger brain size across 36 species of birds and mammals. Our own work has now resulted in an accumulation of evidence that ties successful hand-ax-making to brain systems for self-control and future planning—providing a direct link with this comparative evidence of brain-size evolution across species.

Besides demonstrating motivation and self-control, the toolmaker must achieve a depth of understanding about the characteristics of the stone being worked that is very difficult to obtain through self-teaching. The learning curve for knapping follows a staircase pattern: most of the time you just need to practice and consolidate skills, but every once in a while, a bit of advice takes you to the next level. Although it is sometimes possible to discover tricks of the trade of stone toolmaking independently, there is a real advantage to learning from others.

One good way to learn is simply to watch. Although calling someone a good imitator can be taken as an insult, comparative psychologists have come to recognize faithful copying as a pillar of human culture. Work by Andrew Whiten of the University of St. Andrews in Scotland and many others has shown that apes have some ability to imitate but nowhere near the compulsive, high-fidelity copying skills of human children and adults.

Is imitation on its own enough? You might be able to figure out chess by watching enough games, but it would be a lot easier if someone explained the nuances of strategy and tactics. What we want to know is whether this is also true of stone toolmaking and other prehistoric skills. Thomas Morgan of the University of California, Berkeley, and his colleagues recently conducted a stone-toolmaking experiment to examine how knowledge passes from one person to the next. They showed a significant learning advantage when teaching used language instead of simply demonstrating a skill. Further experiments along these lines might one day help answer the great mystery of when and why human language evolved.

Teaching is not the only possible connection between toolmaking and language. Neuroscientists recognize that most regions of the human brain perform basic computations related to a variety of different behaviors. Take, for instance, 19th-century anthropologist Paul Broca's classic "speech" area in the left inferior frontal gyrus.

Since the 1990s new research has shown that Broca's area contributes not just to speech but to music, mathematics and the understanding of complex manual actions. This recognition has reinvigorated the long-standing idea that toolmaking, along with the human propensity to communicate through gestures, may have served as pivotal evolutionary precursors to language. This idea has been most fully developed by Michael A. Arbib of the University of Southern California, for example, in his 2012 book *How the Brain Got Language*.

Imaging studies hint that neural circuits used in toolmaking were co-opted by the brain for primitive forms of communication.

The results of our own imaging studies on stone toolmaking led us recently to propose that neural circuits, including the inferior frontal gyrus, underwent changes to adapt to the demands of Paleolithic toolmaking and then were co-opted to support primitive forms of communication using gestures and, perhaps, vocalizations. This protolinguistic communication would then have been subjected to selection, ultimately producing the specific adaptations that support modern human language. Our ongoing experiments, aside from building a massive mound of broken flint, will allow us to put this hypothesis to the test. SA

MORE TO EXPLORE

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