doi:10.1093/scan/nsp054 SCAN (2010) 5, 180–187

The re-tooled mind: how culture re-engineers cognition

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One of the main goals of cognitive science is to discover the underlying principles that characterize human cognition, but this enterprise is complicated by culturally-driven variability. While much fruitful work has focused on how culture influences the contents of cognition, here I argue that culture can in addition exercise a profound effect on the *how* of cognition—the mechanisms by which cognitive tasks get done. I argue that much of the fundamental processes of daily cognitive activity involve the operation of *cognitive tools* that are not genetically determined but instead are invented and culturally transmitted. Further, these cognitive inventions become `firmware', consituting a re-engineering of the individual's cognitive architecture. That is, ontogenetic experience from one's cultural context serves to re-tool the developing mind into a variety of disparate cognitive phenotypes. Drawing on several mutually isolated literatures, I advance four claims to the effect that cognitive tools (i) are ubitquitous in everyday cognition, (ii) result in reorganization of the neural system, (iii) are founded in embodied representations and (iv) were made possible by the evolution of an unprecedented degree of voluntary control over the body. I conclude by discussing the implications for the agenda of cognitive science.

Keywords: culture; evolution; embodied cognition; plasticity

An implicit goal of cognitive science is to discover universal principles of human cognition—the blueprint for our shared cognitive architecture. This goal rests on an assumption that, given very broadly 'normal' developmental conditions, our shared modern human genotype results in a more or less consistent cognitive phenotype.

The human lineage diverged from that of the chimpanzees and bonobos a mere 6 million years ago, and within that time span modern *Homo sapiens* emerged with a host of extraordinary cognitive characteristics. This is a remarkably short period of evolutionary time for such radical change to take place. Tomasello (1999) offered a provokative explanation: most of uniquely human cognition is not genetically coded for, but rather has been invented, refined and built up over historical time via the process of cultural transmission. He argued that what makes humans different from our closest relatives is one fairly simple genetic advance—the ability to use social cognitive abilities such as imitation and understanding others' intentions to drive behavioral change and learning. This learning is cumulative across generations, and according to this proposal, such cumulative learning accounts for all other uniquely human cognitive characteristics.

Since then, evidence continues to grow that humans possess a unique cooperatively-based (as opposed to the chimpanzees' competitively based) social cognition that allows a particularly rich form of social learning and cultural transmission (e.g. Warneken and Tomasello, 2009). However, one aspect of the original 1999 proposal cannot hold up: what is universal about uniquely human cognition—abilities shared by all humans but not shared by other apes, such as symbolic representation, complex advanced planning, music-making, the propensity for decorative arts, the ability to shape artifacts according to a mental template, and of course language—cannot be ascribed to cultural accumulation. There is simply too much cultural diversity in the human species, too many isolates, too much historical variation and divergence. There is no single trajectory of accumulated cultural expertise that can account for univeral human cognitive abilities.

Nevertheless, in this article, I will argue for a variant of Tomasello's claim. While cultural accumulation cannot explain human cognitive universals, it is nevertheless a highly important and neglected source of determining the adult cognitive phenotype. The consequence of this, if true, however, is that cognitive phenotypes will differ across cultures, sub-cultures and even more local groupings such as families. Thus, the implicit goal of cognitive science stated above—to identify the blueprint of human cognition—faces a profound challenge.

There are of course many ways that culture influences the *contents* of cognition. This can be seen particularly clearly in the domains of perception, memory and conceptual structure, via principles such as directed attention, pattern recognition, chunking, schemas and reconstructive memory, all of which can be driven by cultural values and practices (Astuti *et al.*, 2004; Levinson, 2007). Argumentation over the extent of such effects has a long and rich history (e.g. Cole and Scribner, 1974).

Received 8 March 2009; Accepted 19 November 2009
Advance Access publication 12 January 2010

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Here I address a different role for culture, one in which culture alters the *how* of cognition—the mechanisms by which cognitive tasks are accomplished. The term *cognitive technology* was recently introduced by Frank and colleagues to capture the phenomenon of number vocabulary as a cultural invention that shapes how people think about number concepts (Frank *et al.*, 2008). In this article, I expand on this idea to capture a widespread process of cultural transmission of cognitive practices. The effect of these on human cognition is, I will argue, quite profound. It amounts to nothing less than a re-engineering of the cognitive system over the life of the individual, a process I will call *cognitive retooling*.

Making the case that cognitive retooling is a substantial force in determining the cognitive phenotype will involve four parts: first, a plausible argument that invented cognitive practices are a widespread phenomenon in ordinary cognition; second, evidence that sufficient neural plasticity exists so that acquired cognitive tools can indeed re-engineer the system; third, a functional-level mechanism to account for how culture-specific cognitive tools are built; and fourth, an evolutionarily grounded explanation of why cognitive retooling exists in humans but not, to any remarkable extent, in other animals.

CLAIM 1: COGNITIVE TOOLS ARE UBIQUITOUS

A physical tool is an invention that expands our ability to manipulate and shape our physical world. Such tools need not be high-tech—our physical capabilities are extraordinarily expanded by access to a longbow, a chisel, or a needle and thread. However, such tools must be invented by someone, and once invented, the skill to create and employ them must be transmitted from person to person for their use to persist (cf. Henrich, 2004). In short, the specific behaviors of tool creation and tool use are not part of our natural behavioral repetoire.

Similarly, humans are capable of inventing cognitive tools: techniques for accomplishing particular cognitive tasks that are not part of our innate cognitive architecture, that can fundamentally change how we think, and that can be transmitted from person to person. If instances of cognitive retooling are sparse and isolated—restricted, say, to lifelong fanatics of chess or crossword puzzles—then the consequences for understanding human cognition are perhaps not noteworthy. Instead, as I will suggest in this section through a range of examples, cognitive retooling is a ubiquitious and everyday phenomenon.

Representations of number

The case of number representation is a good first example of invented cognitive practice. Frank *et al.* (2008) consider the extreme case of a culture, the Amazonian Pirahã, that lacks words for number, and other authors have studied cultures with very limited number systems (e.g. Pica *et al.*, 2004; Butterworth *et al.*, 2008); but even within cultures that have counting numbers, there are a variety of further tools that change how people represent and manipulate numbers. Examples include use of the spatially extended number line giving rise to the SNARC effect, in which responses are faster to small numbers on the right side of space and large numbers on the left side of space (Dehaene *et al.*, 1993); finger-counting and other body-based counting, which is done differently in different cultures, resulting in different base systems (Selin, 2001) and also resulting in different embodied representations of number (Domahs *et al.*, 2008; Fischer, 2008); Arabic numerals, with their key features of a positional system and the use of zero (Pettersson, 1996), and the effects this system has on visualizing and manipulating numbers; methods taught in school for arithmetic with large numbers, such as long division and partial-sums addition; the performance of these same arithmetic operations by persons who are skilled in using an abacus (Miller and Stigler, 1991; Hatano, 1997; M.C. Frank and D. Barner, submitted for publication); and again the performance of these same operations by child street-vendors in Brazil or tailors in Liberia using 'street mathematics' involving the manipulation of groups of objects (Reed and Lave, 1981; Nunes *et al.*, 1993). One thing in common among all these examples of representing number is that their use results in the activation of different mental images, different computational procedures and different mental resources employed. Even when a physical manipuland, such as an abacus, is used, this arguably becomes the basis of a mental representation that is activated during mental computations even when the physical tool is absent. The end result (an accurate count, or a correctly performed arithmetic operation) may be the same for a person working in base 10 or 8, a person imagining an abacus or a person mentally computing partial sums, but the cognitive activity involved is very different.

Spatial representations of time

Time is another domain in which cultures vary in their representational techniques, but a common thread is mapping time onto space (e.g. Ishihara *et al.*, 2008). Linear, circular and block or matrix arrangements are used to represent years, months, weeks, days and hours. Signed languages are rich in the use of spatial representations of time, with American Sign Language, for example, using three different time-lines for different narrative purposes, as well as a 'calendar plane' (Emmorey, 2002). A particularly interesting cross-cultural variation in representing time is the use of space in front of and behind one's body to represent the future and past. The case of the Aymara people of western South America is well-known for their representation, both linguistically and cognitively, of the past as in front of the body (where it can be seen) and the future as behind the body (where it cannot be seen), thus reversing the pattern used in most cultures (Núñez and Sweetser, 2006). In addition to culturally shared representations of time, many people develop idiosyncratic systems for using space to represent time, visualizing the year as a circle, for example, or centuries laid out in rows (e.g. Price and Mentzoni, 2008).

Maps

Like an abacus, a map is a physical tool that can become internalized to form the basis of a cognitive tool. It is known that processing spatial navigation information from a survey perspective is cognitively distinct from, and recruits different brain areas than, a route perspective (e.g. Shelton and Gabrieli, 2002). A culturally-encouraged reliance on maps may thus alter how navigation is performed. This may occur in specific instances, by helping to build up a spatial overview of a region that can then be accessed mentally for a particular journey when the map is no longer present; and in a general sense, by encouraging greater facility with, and reliance on, survey perspectives rather than route perspectives.

Writing and literacy

The effect of literacy on the visual perception of writing is of course massive. The brain reorganizes to specialize in this tremendously over-practiced visual pattern recognition task (Blakemore and Frith, 2005, Chapter 5). However, the ability to read and write may also have effects on higher-level domains of cognition, particularly when it is used as an aid to on-line task processing. A memory retrieval task, such as trying to remember the names of the planets, or items for a shopping list, benefits from an external, continually accessible record of items already retrieved. As another example, any task involving manipulating or examining words and sentences benefits in the same way from an external record, as when polishing a piece of prose, scanning the meter of a line of poetry, or diagramming the structure of a sentence (cf. Wilson, 2008). Writing can also incorporate spatial information, for example when generating two contrasting lists in separate columns, diagramming the hierarchy of an organization's leadership, or creating a flow-chart when roughing out a computer program. Further, it is plausible that experience with such tasks alters the way that we approach such tasks even in the absence of the written record. Consider, for example, the intuition of many desk-job people that 'I can't think without a pen in my hand'. Even if actual writing does not take place, the pen in the hand primes a particular way of thinking.

Musical literacy and musical cognition

There is growing evidence that there are innate, universal principles of music that are shared across the world's cultures (see Wallin *et al.*, 2000, for review); but at the same time, cultures also develop very different musical styles and skills, layered on top of that shared substrate. Being a musician involves much more that the physical skill of playing one's instrument. It may involve familiarity with musical notation; a vocabulary of terms for melody, harmony, chords, chord progressions and so on; and the ability to use one's knowledge of playing an instrument when listening to and parsing music played by someone else. This form of cognitive retooling may be particularly important for composers, who must be able to imaginatively simulate the activities of, and relations among, several instruments or musical lines at once (cf. Wilson, 2008, page 382).

One point to notice for all the examples above is that persistent use of any of these methods will result in engrained procedural knowledge that differs from that of a person without such experience. In the same way that a person who knows how to ride a bike or play a videogame possesses procedural knowledge that is absent in a person without such ability, so too cognitive tools consist of developed skills, resulting in differing skill profiles across individuals.

This claim may at first sound trivial, amounting to a claim that expertise exists; but its import for understanding cognitive functioning has not generally been appreciated. Research on skill-learning and expertise has primarily been conducted in the context of understanding how skills are acquired. What has been neglected is the fact that when the experiment is done, or when the real-life skill has been mastered, it leaves behind a permanently changed cognitive system. This may not matter much in the case of learning a single video game or a strategy for solving Sudoku; but the cumulative effect of a lifetime of numerous expertises may result in a dramatically different cognitive landscape across individuals.

CLAIM 2: USE OF COGNITIVE TOOLS ALTERS NEURO-COGNITIVE ARCHITECTURE

The force of the claim of cognitive retooling is more than just that humans find new ways to do cognitive tasks. Instead, the claim is that the use of such cognitive tools actually alters a person's cognitive architecture. The most direct way to demonstrate this is with evidence of alterations to brain systems as a result of prolonged use of particular cognitive tools.

The case of number representation again provides a useful showcase example of how such alteration can happen. Substantial evidence shows that humans (and cetain other species) universally share two systems for representing number (for reviews, see Feigenson *et al.*, 2004; Dehaene, 2005; Ansari, 2008). One is a system for estimating approximate quantities, and follows a ratio principle of increasing imprecision as the quantities involved become larger. This system appears to be based in the intraparietal sulcus (IPS) in both humans and monkeys (Fias *et al.*, 2003; Venkatraman *et al.*, 2005; Castelli *et al.*, 2006; Tudusciuic and Nieder, 2007; but see Kadosh *et al.*, 2008). The second system is for precisely individuating small quantities of items, with an upper bound of approximately four items. This system is not clearly associated with a particular brain area, and instead may represent a basic principle of object individuation in the visual system (Feigenson *et al.*, 2004).

In addition to these two systems, of course, various cultures have systems for representing larger quantities with exact precision, as discussed in the previous section. Strikingly, for the present purposes, these precise counting and calculation systems appear to be grounded in and exploit both of the pre-existing quantity systems (see Feigenson *et al.*, 2004, for review). For example, the IPS is activated in quantity comparison tasks using both symbolic numerical stimuli and visually presented sets of items (Fias *et al.*, 2003; Venkatraman *et al.*, 2005), and has also been implicated in both acquired dyscalculia (Dehaene and Cohen, 1997; Delazer and Benke, 1997), and developmental dyscalculia (Isaacs *et al.*, 2001; Molko *et al.*, 2003). The system for precisely enumerating small sets also is implicated in developmental dyscalculia (Bruandet *et al.*, 2004), indicating that it too plays a role in developing more sophisticated calculating abilities.

In addition, there is evidence that learned counting and calculation systems recruit motor areas involved in the planning of finger movements (Andres *et al.*, 2008). Thus, we see the exploitation of three fundamental brain functions—visual object individuation, visual quantity estimation and control of a set of countable effectors—as components for an acquired cognitive tool.

Even more striking, different brain areas have been found to be activated by the use of two different strategies for solving mathematically equivalent algebraic problems (Sohn *et al.*, 2004; see also Lee *et al.*, 2007). When subjects were given a word problem such as 'Brian earns \$7 an hour and gets \$9 tips', and then cued with additional information for solving such as 'hours = 3', activation was found in left prefrontal regions. In contrast, when subjects were given an equation such as '$7H + 9 = E$' and cued with '$H = 3$', activation was found in posterior parietal cortex. This was in spite of the fact that behavioral results for the two conditions were indistinguishable. This exemplifies the theme of the present article that equivalent end results can be the consequence of very different cognitive processes to arrive at those results.

A related example is the case of expert musicians. Like the case of number, a basic musical ability may exist in the brains of naive humans (Wallin *et al.*, 2000), but highly complex additional systems have been invented by various cultures, and are therefore acquired skills in the individuals that use them. Experts show consistent changes in brain areas that acquire these functions, such as the left planum temporal (Schlaug *et al.*, 1995; Takashi *et al.*, 2001) and prefrontal cortex (Chen *et al.*, 2008).

Further evidence comes from individuals who have unusual experience with spatial processing. London taxi drivers famously must complete years of rigorous memorization of the streets of London before obtaining their licenses, and their subsequent years of on-the-job experience give them an astonishing ability to navigating between any two points, however obscure, within the city. Several studies have shown that this ability is associated with changes to grey matter in the hippocampus, changes that cannot be explained by the act of driving, self-motion from riding in a vehicle, stress, or preexisting individual differences at time of career choice (Maguire *et al.*, 2000, 2006). Furthermore, there is a striking and counterintuitive finding that London taxi drivers show *reduced* ability to acquire new spatial information, suggesting that a degree of neural commitment has occurred (Maguire *et al.*, 2006).

Another intriguing source of evidence is the case of spatial navigation in four dimensions. Even though humans evolved to navigate in a 3D world, Aflalo and Graziano (2008) have demonstrated that, over many weeks of practice with a 4D gaming environment, subjects can develop competence with navigating in 4D. This includes the ability to perform the 'shortcut test' by pointing directly to one's starting position after several changes of direction, showing that the subjects are not merely learning rules for local navigational decisions. Aflalo and Graziano (p. 1067) point out that mathematicians and gamers claim to be able to think in 4D, and these results give weight to such claims. Although this line of research did not directly examine brain functioning in the subjects, it is nevertheless a striking example of a profound re-tooling of what might otherwise be thought to be a hard-wired mechanism for representing spatial relationships.

Another example that challenges our assumptions about basic neural functions is a recent line of research on the effects of prolonged meditation practice (see Lutz *et al.*, 2008, for review). While Western clinical psychologists have tended to focus on the emotional benefits of meditation, this research has examined the effects of meditation on the attentional system, including specific brain areas implicated in selective attention, sustained attention and conflict monitoring. Studies show not only that there are changes in the activations of these areas during or just after performing meditation, but that long-term practitioners show both behavioral and brain-imaging differences on attention tasks even when not meditating.

What all of these examples suggest is that brain plasticity in response to particular cognitive practices is widespread. While brain areas have strong predispositions to perform certain cognitive functions, there is also a considerable 'fringe of variability' (Dehaene, 2005) that allows each individual's experiences and learned cognitive habits to rewire the system.

CLAIM 3: COGNITIVE RETOOLING EXPLOITS BODY REPRESENTATIONS

In the previous section I considered the argument for neurological plasticity allowing retooling of the brain in response to experience. But this does not explain what people are doing, at a functional level, when they invent, practice and use a cognitive tool. Can we say anything more substantive about the resources, the raw materials, from which new cognitive tools are built? Here I propose that many, perhaps most, examples of cognitive retooling are fundamentally grounded in *embodied cognition*, the use of perceptual, motor and spatial representations—representations of the body and the physical world—to facilitate cognition. According to this argument, cognitive retooling consists by and large of finding new ways to use sensorimotor simulations to represent information.

To make this case requires first sketching the arguments that have been made in the literature on embodied cognition. In particular, one branch of the embodied cognition literature deals with *off-line embodiment*, or *simulation*, in which body-based representations are decoupled from interaction with the immediate environment, in the service of cognitive tasks that do not involve the here-and-now (see Wilson, 2002, for review). This includes running sensorimotor simulations of situations that are concrete and physical, though not immediately present, including the past, the future, the physically distant and the imaginary.

But more important for the present purposes is that these sensorimotor simulations are also used to represent abstract concepts and relationships, by way of analogical mappings. Humans routinely map abstract concepts onto similarly structured concepts that are concrete and physical (e.g. Barsalou, 2005; Gallese and Lakoff, 2005; Zwaan and Taylor, 2006). One example of this is the use of hand-gestures to support cognitive processing (e.g. Goldin-Meadow, 2006; Broaders *et al.*, 2007). Another example is the use of systematic domains of metaphors in ordinary language, such as *communication is sending, time is money* and *more is up* (Lakoff and Johnson, 1980). An important empirical demonstration of the psychological reality of these metaphors is the action-sentence compatibility effect. In this effect, movement towards or away from the body is facilitated when processing sentences that express literal concepts of transfering, such as 'Mike handed you the pizza', and also for metaphorical concepts of transfering, such as 'Liz told you the story' (Glenberg and Kaschak, 2002). In addition to these examples in everyday language and cognition, mappings from the abstract to the concrete are also widely present in more formalized representational systems that are usually learned through formal education. These include spatial representation of virtually any measurable dimension in the form of graphs and diagrams in math, logic, statistics and physics. The embodied cognition literature argues that much, perhaps all, of abstract thought is grounded in body-based resources in these ways.

This line of argument is particularly relevant to cognitive retooling, wherein pre-existing cognitive resources are co-opted for new uses. If we consider the examples given earlier in this article—physical representations of number, spatial representations of time, musical notation, and so on—we can see that concrete representations of the abstract loom large. The benefit of cognitive tools is that they reconfigure information into some new format that makes it easier to code, store, and manipulate the information, and to see relations among the parts. Everything we know from the embodied cognition literature suggests that these easier formats will be concrete and enactable with one's own body. I propose that cognitive retooling depends to a large degree on adapting body-based representations to new uses.

This account imposes predictions as to what forms cognitive retooling can take. Specifically, invented cognitive practices should be constrained by principles of embodiment—the capabilities and limitations that the human body and its sensory and perceptual systems impose when the body is used as a representational device. The flexibility of representation confered by this system is not arbitrary and infinite.

This same point—that the brain's representations of the body and the sensory world will constrain cognitive retooling—can also be seen through the lens of neural plasticity. Specifically, the fact that large territories of the cerebral cortex are specialized for processing perceptual information, motor planning and perception–action links, suggests that the embodied principle of cognitive retooling proposed here is inescapably rooted in the biology of brain plasticity. Rather than suggesting that neural plasticity is infinite in response to experience, the cognitive retooling hypothesis is committed to the claim that retooling will only be possible within the constraints of the brain's ability to adapt its predispositions and pre-existing functions to new but related uses.

A DETOUR: LANGUAGE AND COGNITIVE RETOOLING

One substantial exception to the principle offered in the previous section may be the case of language. Arguably, words themselves can be cognitive tools, when they are considered as inventions that stand for new concepts and facilitate the mental maintenance and manipulation of those concepts. Indeed this is the type of case that Frank *et al.* (2008) were considering when they coined the term *cognitive technology*. In Frank *et al.*'s view, the existence of number words in a language facilitates memory for number, enumeration of objects and other forms of mental manipulation that involve number. Thus, in a modified form of linguistic relativity, having or lacking words for concepts can deeply alter our cognitive relationship to those concepts.

As with other cases of cognitive tools, this may be easiest to see with highly technical topics acquired through formal education. Understanding advanced physics, for example, would impose an impossible cognitive load if one did not acquire the technical vocabulary at the same time as learning the concepts. Terms such as *angular momentum*, *diffraction*, or *time dilation* act like promisory notes that can be cashed in for their more basic component meanings as needed, but can also be grabbed quickly and held in working memory easily, and can themselves be used as elements for still more complex concepts. In addition to these technical examples whose use is restricted to a small fraction of the population, many everyday words may also carry cognitive load in a similar fashion. What is particularly interesting about the case of the Pirahã is that a very basic class of words, one that might have been thought to be universal, instead turns out to be an invention, with all the consequences that attend the having or lacking of a cognitive tool.

Words as labels for concepts, then, may be an important class of examples of cognitive retooling. But is there a reasonable sense in which these are embodied? The answer, perhaps surprisingly, may turn out to be yes. Words are physically produced by our bodies, spoken with our vocal apparatus or, in the case of signed languages, articulated with the hands. Thus, mental representation of a word (or sign) involves motor resources. This might seem to be a degenerate case of embodied thought, since, in general, the physical production of the word or sign is not relevant to the meaning being represented. [It's true that many signs, and some spoken words, are *iconic* in the sense that the physical form has an isomorphic relationship to the meaning on at least some dimensions. However, this may have more to do with the historic development of the language than with any psychological importance of the iconicity (Newport and Meier, 1985)]. However, one of the substantial benefits of words as cognitive tools (as opposed to communicative tools) is their contribution to working memory—the ability to quickly 'tag' a concept and maintain it in memory at little cognitive cost while performing related operations. In this respect, the physical, embodied aspect of words is crucial. Working memory operates precisely by off-loading information onto the motor system via articulatory rehearsal (Wilson, 2001). In fact, this arguably underlies the cognitive differences in thinking about number observed with the Pirahã (Frank *et al.*, 2008). Thus, even the case of linguistic elements as cognitive tools may be, in a useful and meaningful sense, embodied.

CLAIM 4: FLEXIBLE VOLUNTARY CONTROL PERMITTED THE EMERGENCY OF COGNITIVE RETOOLING

If much of uniquely human cognition, including abstract thought, is based on invented cognitive tools that are offline uses of embodied resources, this raises the question of how this form of embodied thought arose in the human lineage. I have recently proposed that a key precondition was flexible, voluntary control over the body (Wilson, 2008).

Most animals interact with the environment via a fairly stereotyped set of actions, the animal's behavioral repertoire. Furthermore, these behaviors are deployed predictably in response to certain types of situations, which we can characterize as the behaviors being *stimulus-bound*. In contrast, humans have an extraordinary degree of voluntary control over their bodies, both in terms of the types of actions and behaviors that can be invented, and in terms of the choice of when to deploy them. This buys two advantages with respect to embodied cognition: the ability to invent new physical tokens that can be used as the basis for mental representation; and the ability break the connection to the immediate environment and engage in embodied thought off-line.

Various non-human species possess some degree of voluntary control over at least one set of effectors, resulting in a range of non-stereotyped behaviors that can differ across individuals and across groups, including behaviors that can plausibly be characterized as playful and creative. Examples include the trunk and the vocal apparatus of the elephant, the snout of the walrus, the vocal apparatus of some bird species, and the hands of primates (Poole *et al.*, 2005; Call, 2008; Lachlan, 2008; Schusterman and Reichmuth, 2008). But in each of these groups, there are also behaviors that lack this voluntary control, such as the vocal calls of primates. Thus, this precondition for embodied cognition may exist in partial form in a variety of species, but humans have taken it to an extreme degree. Humans' voluntary control involves almost every part of the body that is controlled by skeletal muscles (at least with practice, as in wiggling one's ears or rolling one's abdominal muscles in belly dancing); and although humans too have a repetoire of stereotyped, involuntary behaviors, notably laughter and facial expressions of emotion, we also have some ability to mimic these at will (making possible both stage acting and social hypocrisy). In addition, it is unclear whether other animal species have the ability to run their sensorimotor processes off-line, not only at will but also divorced from any immediate situational trigger, thus generating simulations of situations that are not present.

To sum up the claim, then, the evolutionary advance of massively flexible control over the body gave rise to the possibility of embodied simulations, which in turn gave rise to the possibility of cognitive retooling. This has the implication that, in line with Tomasello's claim, what makes human cognition 'smarter' is to a large extent not a collection of evolved cognitive modules for accomplishing all our unique cognitive tricks, but rather the ability to re-engineer our existing cognitive resources in a flexible fashion.

CODA: THE AGENDA OF COGNITIVE SCIENCE

The considerations outlined in this article have several implications for the direction of cognitive science. First, we must consider the fact that most research on human cognition takes place in the context of literate, urbanized cultures with formal schooling. This fact may have distorted our scientific understanding, a point that has long been appreciated for social and emotional aspects of psychology but not to the same degree for cognition. If so, then the need to study isolated cultures before they vanish is as urgent for cognitive psychologists as it is for linguists and others (Ebert, 2005; Evans and Levinson, in press). Cases like the Pirahã may teach us lessons about non-universality of cognitive functions that might otherwise be obscured by shared global influences.

A second point to consider concerns the methods in behavioral research. Cognitive psychologists tend to avoid studies that require either cross-cultural comparisons or prolonged learning, due to the time commitment involved. While cross-cultural research is becoming more common, it faces limitations not only from globalization but also from the fact that it relies on 'natural experiments' of cultures that happen to have adopted different ways of doing things. Meanwhile, learning studies remain relatively neglected. Learning studies are time consuming, and poorly suited to the standard model of undergraduate subjects who participate for one-hour course credits. However, this often leads to an implicit assumption that limits and inabilities demonstrated in laboratory experiments represent hard limits of human cognition. Instead, we must start challenging such assumptions by seeing what the system can do in response to prolonged experience.

A third point concerns the direction of neuroscience as it tackles the increasingly important topic of culture and the brain. While the account offered here predicts that there will be major differences across cultures in how particular cognitive tasks are accomplished, it does not predict re-organization of fundamental cognitive processes, such as the principles that govern perception, memory consolidation and so on. Further, it should also be noted that cross-cultural differences as a result of cognitive retooling will not necessarily appear as coarse differences in brain processing—for example, entirely different brain areas being recruited when the same task is being performed in two different ways. While this may sometimes be the case (e.g. Sohn *et al.*, 2004; see also Lee *et al.*, 2007), in other cases two strategies may recruit the same brain areas (e.g. motor areas, visual representation areas), but differences may be found, for example, in strength of activation in response to task materials designed specifically to interfere with or facilitate one way of accomplishing a task but not another. The lesson here is that neuroscience will be of limited usefulness if employed as a heavy-handed tool; instead, neuroscience approaches to this issue must pay careful and nuanced attention to the specific predictions that emerge from specifical cultural cognitive practices and the representations that they recruit.

A fourth lesson to draw is the goal toward which cognitive science is working. In past decades, cognition was assumed to operate according to a single universal blueprint, and the job of cognitive science research was to uncover this blueprint—to reverse-engineer the universal structure of the human mind and brain. In contrast, an increasing appreciation for the existence of individual differences is moving us towards a more nuanced vision, in which the goal is to understand the shared principles by which individual brains develop into diverse adult minds.

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