

Evolutionary Perspectives on Mind, Brain, and Education

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ABSTRACT— Understanding about human origins informs our understanding of what it means to be human. It is reasonable, therefore, to consider that an evolutionary perspective can provide insight into the nature and processes of human learning and education. This article reviews how ideas about evolution have influenced educational thinking in the past. It then considers how understanding of brain development and function is helping to inspire “new thinking” about evolution. The review converges on a range of benefits that may arise from the inclusion of evolutionary concepts within the field of mind, brain, and education. These benefits include scrutiny of evolutionary neuromyth, reconsideration of the cultural and political status of education, insight into notions of individual difference, and help with stimulating and directing research efforts aimed at improving educational outcomes.

learns to walk before crawling, then this has a detrimental effect on the later development of more complex processes such as language. Treatment might encourage the child to rehearse crawling movements, in order to *repattern* their neural connections and improve their academic progress. Scientific reviews have concluded that the theory is unsupported, contradicted, or without merit (Chapanis, 1982; Cohen, Birch, & Taft, 1970; Cummins, 1988; Robbins & Glass, 1968), and practical approaches based upon such ideas have been revealed as ineffective (American Association of Pediatrics, 1998).

The blossoming of neuroscience in the 1970s raised awareness of how some brain structures appear broadly conserved from species that preceded *Homo sapiens*. In 1978, neuroscientist Paul Maclean described his “triune brain hypothesis” in the National Society for the Study of Education yearbook (MacLean, 1978). Maclean considered the brain to comprise three formations (three “brains”) that reflected our evolutionary past: the reptilian brain (including the brain stem), the paleomammalian brain (limbic system), and the neomammalian brain (including the cerebral hemispheres). Application usually makes the questionable assumption that education can influence which brain is dominating (Nummela & Rosengren, 1986). Maclean’s proposal of “directional evolution,” in which brain parts appear in a manner characterizing human notions of progress, is anthropocentric and difficult to justify. Indeed, all vertebrates demonstrate a brain structure with the three distinct divisions of forebrain, midbrain, and hindbrain. Evolution appears to have proceeded via modifying these three parts rather than constructing each division in an additive and linear manner (Krubitzer & Seelke, 2012). Despite such flaws, Maclean’s theory proliferated in the many “brain-based” learning programmes of the 1980s, cropping up recently in theories of moral education (Narvaez, 2008).

Since the mid-1980s, scholarship on the evolution of the human mind has been dominated by a set of concepts known as “Evolutionary Psychology” (EP), and also referred to as the “Tooby and Cosmides tradition” (Panksepp & Panksepp, 2000) or “Santa Barbara School” (Heyes, 2012a). This asserts that the brain comprises a set of computationally distinct modules which support core cognitive domains, each evolved

EVOLUTION AND EDUCATION

There is a long history of evolution influencing educational thought. In 1881, Charles Darwin wrote to the American Social Science Association discussing potential childhood studies that “would probably give a foundation for some improvement in our education of young children” (Darwin, 1882). Many contemporaries made their own interpretation of Darwin’s ideas, which also inspired Haeckel (1866) to argue that ontogeny (individual development) recapitulates phylogeny (the development of the species). Long after mainstream science had abandoned recapitulation theory, its influence continued to trouble education. The Doman-Delacato theory of development proposed that efficient neurological functioning required the acquisition of specific motor skills in the correct evolutionary order (Doman, 1968). According to this view, if a particular developmental stage is skipped, such as when a child

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to enhance survival or reproductive success during the Pleistocene period. Claims for the existence of brain/mind modules are often debated within cognitive neuroscience (see Colombo, 2013 for review). These claims have chiefly centered on basic sensory/perceptual and motor processes, with continuing contention around, for example, whether we possess a genetically ingrained cortical region for face recognition (Cohen & Tong, 2001; Kanwisher & Yovel, 2006). Evolutionary psychologists, however, took things further by suggesting selection (as ingrained genetic adaptations) of various domain-specific abilities including an aptitude for folk psychology (to understand issues such as kinship), folk biology (to identify fauna and flora when hunting and gathering), and folk physics (to navigate and construct tools). EP perspectives propose these specializations still bias modern human behavior.

In the last decade, Geary (2008, 2010) has proposed that the EP approach can provide a set of premises and principles for an evolutionarily informed science of education. Geary suggests a Pleistocene-derived bias in our learning processes that results in a widening gap between accumulating cultural knowledge (referred to as “biologically secondary knowledge”) and the forms of folk knowledge and abilities that emerge with children’s self-initiated activities (“biologically primary knowledge”). Geary sees education as addressing this gap, that is, by ensuring that a core set of biologically secondary skills and knowledge is common to all society. The EP approach, he argues, helps explain why children often find secondary types of learning (e.g., reading) more difficult than primary types of learning (e.g., speaking), and emphasizes the importance of effortful learning in educational contexts. Others have taken Geary’s ideas and applied them to working memory (Paas & Sweller, 2012), learning (Schuler, Scheiter, & Gerjets, 2012), problem-solving (Retnowati, Ayres, & Sweller, 2010), and child development (King & Bjorklund, 2010). This application of EP to education has been criticized for lacking power and falsifiability (Halpern, 2008), and for its lack of biological evidence (Ellis, 2008). Initial concerns about EP itself focused on using the archeological record to generate testable psychological hypotheses about modern behavior. This, it has been argued, may create evolutionary “just so” stories whose criteria for acceptance are too loose, with the option of substituting adaptive stories until one fits, without due consideration of entirely different kinds of explanation (Buller, 2005; Gould & Lewontin, 1994). New voices of criticism have arisen from the neuroscience community, where some consider EP to be “potentially idle speculation” until a broader consideration of evolution of the mind/brain is included (Panksepp & Panksepp, 2000, p. 113). The plastic nature of the cortex (as evidenced by the neural function of damaged regions emerging again in adjacent regions), does not easily support the concept of genetically governed modules dedicated to very specific types of environmental knowledge such as folk biology and folk

physics. Gene activity, interacting with environmental and behavioral influence, biases the localization of function to particular regions and to develop in particular ways, but there is scant evidence to suggest that the specificity of this genetic bias extends to determining EP-type modules for flora, kinship, and so on. Modern brain/mind patterns that are apparently intrinsic may result from socially and culturally acquired environmental and behavioral influences during an individual’s development. These arguments echo a more established modularity debate within cognitive neuroscience. For example, the well-researched “theory of mind” (TOM) module (Frith, Morton, & Leslie, 1991) remains contested by those adhering to a more neuroconstructivist perspective of development (Westermann et al., 2007). However, the specificity and Pleistocene focus of EP modularity is more contentious than the hypothesized existence of a TOM module, with evidence of ancestral precursors of TOM behavior amongst other members of the primate family (Buttelmann, Schutte, Carpenter, Call, & Tomasello, 2012; Call & Tomasello, 2008). Modularity arguments aside, and assuming a Pleistocene-related bias in present-day behavior could be proven, would its magnitude be of educational significance? It seems unlikely such bias would compare in size with that arising from our motivational and emotional systems, whose influence on memory is well documented (e.g., Shohamy & Adcock, 2010). Therefore, until there is convincing evidence of their efficacy in education, EP concepts may have difficulty contributing central premises and principles to an evolutionary perspective on education that is comfortably aligned with contemporary neuroscience.

In contrast to EP, a more foundational approach to including neuroscience perspectives in evolutionary thinking has focused on similarities in brain, behavior, and various basic psychological features across species (e.g., Herculano-Houzel, 2012; Heyes, 2012a; Panksepp, Moskal, Panksepp, & Kroes, 2002). An important argument characterizing this approach is that the identification of uniquely human features of brain development and function can only be confirmed by excluding their occurrence in other related species. This can provide a basis for considering how the human brain diverged from these other species over deep time, including other primates that are both extant and, using fossil-based estimates of metrics such as brain size, now extinct. Understanding of our unique genetically based characteristics can be combined with archeological evidence and insight to suggest when such changes occurred and relate these to contemporaneous behavioral changes in the history of our rise to top predator. The hope here is that such an interrelation of the evidence across disciplines may help create a narrative of human evolution in terms of brain and mind that provides insights into the neural and mental processes underlying our potential as a species, and helps illuminate the role of education in realizing this potential.

The rest of this article adopts this foundational approach by reviewing what is special about the human brain and considering how it has evolved across deep time. It will then focus on the “new thinking” regarding the genetic and cultural acquisition in prehistory of uniquely-human symbolic abilities (spoken language, literacy, and numeracy) and explore how these insights may impact on the emerging field of mind, brain, and education.

WHAT MAKES OUR BRAIN SO SPECIAL?

The human brain is often celebrated as amazing, but how much more amazing is it than those of other species? Our brain mass is several times smaller than that of African and Asian elephants (Shoshani, Kupsky, & Marchant, 2006) and a range of different whales (Marino, 1998). Our brains do, just, have the largest amount of cortex as a percentage of whole brain mass (around 76%), but with chimpanzees (Stephan, Frahm, & Baron, 1981), horses, and short-finned whales (Hofman, 1985) achieving 73, 75, and 73%, our lead is hardly commensurate with the status we assign to our cognitive abilities. Cortical folding, or gyrification, has long been considered a means to accommodate an increasing cortical surface within the same confined space (Welker, 1990) and might be another way in which humans distinguish themselves from other primates. However, gyrification has been shown to follow order-specific rules, with no significant difference in gyrification as a function of brain size between extant hominids and old world monkeys, such as the baboon and mandrill (Zilles, Palomero-Gallagher, & Amunts, 2013).

A case for our supremacy might justifiably use more sophisticated measures. Brain size does not scale up like other body parts, so perhaps we should take account of the absolute size of an animal. Over a range of animals, a power law emerges when brain size is mapped against body size, with deviation from this trend termed the encephalization quotient (EQ). Such deviation might suggest extra neural processing capacity beyond that required for monitoring and coordinating a larger body and so EQ has been used to represent an external measure of animal intelligence. Based on EQ, the human brain has around 7 times greater brain:body mass ratio than expected for a mammal, and threefold greater than expected even for a primate. However, a study of the relation between EQ and cognitive ability across nonhuman primates shows little predictive power between EQ and intelligence and suggests brain size is, after all, a better predictor in this context (Deaner, Isler, Burkart, & van Schaik, 2007).

The work of Herculano-Houzel and her colleagues reveals an order-specific relationship between neuron density and brain size (Herculano-Houzel, 2012; Herculano-Houzel et al., 2011; Sarko, Catania, Leitch, Kaas, & Herculano-Houzel, 2009). Relative to other mammals, primates accommodate

neurons more efficiently with size across species, such that a new species can acquire a 10-fold increase in neuron number through only a 10-fold increase in brain size if it is a primate, compared with a 50-fold increase in brain size required for a rodent (Herculano-Houzel, 2012). The human brain resembles a scaled-up version of other extant primate brains (Herculano-Houzel, 2009) with a larger cortex and consequently the greatest population of neurons of all animals (estimated by Herculano-Houzel at 86 billion¹ compared with, for example, a gorilla's 33 billion neurons).

So, despite our sense of primacy, the human brain does not appear biologically extraordinary in relation to those of other species (Herculano-Houzel, 2012), with our chief biological advantage arising from our enlarged brain being a primate brain. This advantage may not have been unique to *H. sapiens*. The interpretation of brain architecture from a fossilized skull is very limited, but it can provide a reasonable estimate of the size of the living brain that once occupied it (Holloway, Sherwood, Hof, & Rilling, 2009). Application of the primate neuronal equation to the fossil record suggests archaic *Homo* members such as *heidelbergensis* and *neanderthalensis* had reached capacities of 76–90 billion neurons, which are within the range of variation found in modern humans (Herculano-Houzel & Kaas, 2011). Across mammalian orders, it also seems that, even when the cortex expands and dominates brain volume, the ratio of neurons in the cortex (associated with higher order cognition) to those in the cerebellum (associated with sensorimotor coordination) remains roughly constant. This is important because the neocortex ratio (size of cortex to rest of the brain) has also been used to suggest a radical difference between ourselves and other primates. Yet, increasing this ratio may not reflect a change in distribution of neurons or suggest a shift toward higher level processing (Herculano-Houzel, 2011).

AN EVOLUTIONARY NARRATIVE

Before Mammals

To appreciate the relevance of deep time evolution to learning, we might begin in the Devonian period (400 Mya), when early fishes exhibited the basic plan of the basal ganglia (BG; Reiner, 2009). The BG play a key role in the planning, initiation, and execution of movement, and in the learning of these processes. The human BG contain a range of features common to the BG equivalent of reptiles and birds, and other mammals (Smeets, Marin, & Gonzalez, 2000). These include the nucleus accumbens, ventral pallidum, and ventral tegmental area which are critical to motivational and learning processes such as the association of action and reward in reinforcement learning. BG function is crucial for more visceral motivations (e.g., food and sex) but has also been found to underpin behaviors including foraging, habitat selection, and

aspects of social behavior shared by many creatures (O'Connell & Hofmann, 2011).

It is here in the subcortex that we also find some clearly defined “lower” modules whose basic function is relatively invariant across individuals and species (e.g., fear response, reward learning, and approach motivation). These have such behaviorally important bidirectional links to the human cortex that analysis of many of our so-called “higher” brain functions would be misleading if they focused solely on cortical function (Panksepp & Panksepp, 2000). In some sense, then, Maclean's view of the ancient evolutionary history of some components of the brain retains a type of legitimacy. However, rather than being quasi-independent and ordinarily competing, the function of these subcortical components is closely entwined with that of the higher cortical networks. Indeed, over deep evolutionary time, a major trend has been the increasing involvement of the cortex in the processing of sensory information relayed to the BG (Smeets et al., 2000). For example, our emotional response to receiving social reward is measurable in the BG (Rademacher et al., 2010) but the response of the BG will influence cortical connectivity related to the context of the reward (Shohamy & Adcock, 2010), which in turn can mediate BG response (Nieuwenhuis et al., 2005).

Arrival of Primates

Across the Paleocene–Eocene boundary (55 Mya) rapid climatic changes included widespread tropical and subtropical conditions. Mammals appeared with some emerging primate features, indicating an important point of evolutionary divergence and the imminent birth of our primate family. The Arboreal Theory of Primate Evolution proposed that moving from the ground to the trees resulted in uniquely primate features, suggesting that using forelimbs to climb trees may have led to improved eye–hand coordination (Howells, 1947; Le Gros Clark, 1963). However, it was subsequently noted that other mammals lived in the trees at this time without primate features, and the 1970s heralded a finer grain analysis of the primate evolutionary niche. Cartmill (1974) found that grasping hands and feet are common in animals that habitually forage at the slender ends of branches, allowing their hind limbs to suspend them while forelimbs are free to deal with the food. With the exception of a few primate-like marsupials, primates are the only major taxonomic group of nonflying vertebrates that regularly feed in this way. In 2002, a late Paleocene (56 Mya) precursor to fully modern primates was found in Wyoming, strengthening the proposal that primates first evolved these grasping abilities and then developed convergent forward-facing eyes (not yet evident on this specimen) to penetrate the cluttered forest canopy (Sussman, Rasmussen, & Raven, 2013).

An early line of primate evolution led to tarsiers (small insect-eating nocturnal predators with large eyes) and

anthropoids. The first anthropoids were diurnal visual predators, with later anthropoids (monkeys) evolving larger bodies and diversified diets including fruit and leaves. Many early anthropoids formed social groups, possibly as daylight made communal life advantageous in terms of protection and warnings. Apes arose from anthropoid monkeys around 25–30 Mya to occupy rainforest environments, and one line of apes diverged around 6–8 Mya into a branch leading to chimpanzees, bonobos, and the group of bipedal primates known as the hominins—an ape adapted to a drier climate with grassland and savannah (de Sousa & Wood, 2007). Although earlier candidates for membership of the hominin subfamily exist, it is accepted that archaic humans (australopiths) had arrived by 4–5 Mya (Wood, 2010), still retaining skeletal features required for climbing trees.

Arrival of Genus *Homo* and Brain Expansion

Hominin brain size generally increased over evolutionary time and there is also general consensus that a larger primate cortex supports greater social complexity (Dunbar & Shultz, 2007). However, a range of potential drivers for the increase have been put forward, including climate change, predation, sociality, language evolution, and the opportunities for growth provided by a higher energy diet. Current evidence fails to convincingly identify one key driver of encephalization, suggesting a complex interaction of many factors may explain the underlying trend.

At around 600 cm³, the brain size of the genus *Homo* was already larger than its archaic predecessors by around 30% and capacity increased over prehistoric time to a modern average of 1,330 cm³ (Holloway et al., 2009). While cut-marked bones from Ethiopia suggest stone technology was used by *Australopithecus afarensis* 3.39 Mya (McPherron et al., 2010), the earliest stone tools are 2.5 Mya from Gona in Ethiopia (Semaw et al., 1997) and contemporaneous with the arrival of the genus *Homo* (in its earliest form of *Homo habilis*). After 1.5 Mya, full bipedalism had been achieved (Bennett et al., 2009) and advances in stone technology led to the large cutting tools of *Homo ergaster* and *Homo heidelbergensis* in Africa and Europe (Barham & Mitchell, 2008; McNabb, Binyon, & Hazelwood, 2004) whose qualities are interpreted by some as indicating new social and cultural complexities (Gamble, Gowlett, & Dunbar, 2011, but see McNabb et al., 2004). However, following the initial arrival of this Archeulian technology, advances in tool-making plateaued out until 0.8 Mya. This was despite encephalization continuing with a step-change at the arrival of *Homo erectus* followed by further gradual increase, as if a more archeologically “silent” revolution was gathering pace (Gowlett, 2009). Then the first hearths appeared around 0.8 Mya (Goren-Inbar et al., 2004), ritual defleshing of skulls about 0.6 Mya (Rightmire, 1996; White, 1986) and specialized

production routines for manufacture of flakes around 0.4 Mya (Barkal, Gopher, Lauritzen, & Frumkin, 2003). Prior to these, and other accumulating innovations, it appears possible that brain size was evolving with advances in early or “proto” language, with a long period during which initial advances in protolanguage did not greatly impact on tool technology (Gowlett, 2009).

Rather than arriving suddenly, it is reasonably hypothesized that protolanguage built upon the existing cognitive platform we share with other primates for the production of gesture, as we gradually developed the capacity for more complex, structured signs (Sterelny, 2012). Modern language is often not stimulus-specific (i.e., modern words need not be responses to stimuli in the immediate environment or usually be required to covary with environmental referents). However, it can be argued that the first protolanguages, whether gestural and/or auditory in their resemblance to other primate communications, would have been more tied to these stimuli. Such language would still afford advantages in the here-and-now of hunting. Even amongst today’s hunter-gatherers, learning of hunting skills occurs largely by social learning: observation and imitation in the here-and-now, and only to a lesser extent through formal teaching processes such as instruction, demonstration, and story-telling (MacDonald, 2007). Social learning is demonstrated in other animals. It appears to be mediated by mechanisms of associative learning and recruits many of the same brain regions as asocial learning (Heyes, 2012b). It differs from other types of action learning chiefly with respect to using input mechanisms that are biased toward information supplied by other agents, a bias which can itself be socially learnt (Heyes, 2012a). In other words, there is no need for the core mechanisms of human social learning to have been further shaped by evolution before they provided a basis for the social transmission of accumulating information, including biases that resulted in an increase in the rate of transmission. The sequencing of complex actions for tool use and gesture recruits the same brain regions, and protolanguage development may also have ultimately contributed to the arrival of more sophisticated tool production (Frey, 2008). *H. sapiens* may not have arrived with, or developed further as a species, any radical genetically-ingrained modular advantage specific to social learning or tool use.

Many of the domain-specific skills providing advantage in the Pleistocene (including those identified by EP) could have been driven by the subcortical emotional and motivational systems evolved over deep time. For example, imaging studies suggest human foraging (Daw, O’Doherty, Dayan, Seymour, & Dolan, 2006), competitive foraging (Howard-Jones, Bogacz, Yoo, Leonards, & Demetriou, 2010), and stalking-type behaviors (Howard-Jones, Lloyd, & Bogacz, 2013) are learnt using a prediction error signal, thought to be coded by dopamine uptake in subcortical regions of

the reward system. These learning processes also rely for their success on bidirectional communication with cortical representations of action value and motor patterns for executing the action (Wunderlich, Rangel, & O’Doherty, 2009). Similarly, sharing of rewards with others stimulates greater subcortical reward response when these others are socially valued (Fareri, Niznikiewicz, Lee, & Delgado, 2012), and cortical regions are key to processing facial familiarity and identity (Platek & Kemp, 2009). Since declarative memory formation is related to reward-response, the experience and anticipation of positive food sourcing exploits and sharing would support, and be supported by, the encoding and recall of contextual information such as flora, fauna, and facial information. While the encoding of such information is unlikely to have left a genetically ingrained impression on the cortex of our species, our motivational and emotional systems may bias behavior in ways ill-fitted to a modern environment. For example, the presence of peers has been reported to heighten neural response to potential reward values in risky decision making amongst adolescents (Chein, Albert, O’Brien, Uckert, & Steinberg, 2011). Historically, a plausible benefit of such a bias might be to help young people prepare for hunting and combat, while in today’s society it is cited as a possible cause of adolescent road traffic accidents (Chein et al., 2011).

Anatomically modern *H. sapiens* arrived in Africa around 150–195 kya, but there is little evidence of symbolic behavior and cultural variation in tool manufacture for many more thousands of years, suggesting an overall slow development of symbolism in spoken language and material culture—and not necessarily a continuous one. Symbolism involves the association of culturally shared fictions with facts. Many types of animals can transfer information across generations through learning processes that might be called broadly cultural (e.g., through observation) but symbolic culture is regarded as distinctly human (Knight, 2010). Although the early manifestations of symbolism involved the invention of gods and goddesses, symbolism also allows us to automatically conceptualize a four-legged barking animal when we read the word “dog,” or think that “4” is more than “3.” In this way, it also underpins the numerical and literary abilities by which modern culture, including modern science, has developed. Evidence for symbolically mediated behavior has been found from Africa by at least 100 kya, by around 120–100 kya in the Middle East and around 60 kya in Europe (d’Errico & Stringer, 2011). However, before 20 kya, there is no uninterrupted accumulation of innovations as predicted by a sudden change in human cognitive ability. The slow and discontinuous pace of behavioral change amongst our own species and other hominids with apparently similar neuronal populations suggests a simple increase in computing performance may have been a necessary but not sufficient basis for developing our unique human abilities. Rather, appearances and disappearances of innovation suggest a critical role

of local conditions (e.g., population density and opportunities for contact) in both the emergence and disappearance of symbolism (Powell, Shennan, & Thomas, 2009; Richerson, Boyd, & Bettinger, 2009).

The suggestion here, then, is that modern symbolic culture arose from primates with a sufficiently large population of neurons, already capable of tool-making and sophisticated hunting activities, encountering appropriate local conditions. If such was the case, one might expect other hominid species would have met these criteria and also left evidence of symbolic material culture. Recent findings do suggest that Neanderthals sporadically used red ochre in Northern Europe since around 200–250 kya (Roebroeks et al., 2012). Red ochre has more practical uses but additional and perhaps more compelling evidence for the cultural capacities of Neanderthals arises from their use of feathers (Morin & Laroulandie, 2012), which can more securely be attributed to symbolic purposes. This appears to have occurred at many different sites dating from 100 kya until Neanderthal extinction around 30 kya (Finlayson et al., 2012). Some modest upgrade of our speech potential may also be associated with biologically evolved changes. Extension of the subvocal tract allowed us to increase our vowel range (from around 50 kya in Europe and possibly much earlier in Africa), but many of the configurations of the vocal tract for modern language are already available to nonhuman animals (Lieberman, 2012).

From around 20 kya, the continuous accumulation of nonutilitarian objects provides reasonable grounds for assuming a step change in cultural transmission of knowledge has occurred and for attributing this to the use of more stimuli-independent auditory symbols. One way of thinking about how this step change occurred is to consider the social relationships that were critical for knowledge transfer. Grooming is recognized as the primary mechanism for negotiation of social relationships amongst primates but, as pointed out by Dunbar (1993), grooming is restricted to very close 1:1 interactions. Stimulus-specific auditory and gestural communications can sustain larger social groups but are limited to communicating with those who are present in time and space. Material resources, in contrast, can support communications beyond the temporal and, when portable, the spatial boundaries of the communicator and initial stimulus. In this way, material culture may encourage and support the extension of here-and-now primate sociality to something more symbolic (Coward & Gamble, 2008). Material culture would also have complemented (i.e. supported and be supported by) increased enculturation of children through an “education of attention” (Ingold, 2000). In existing communities without formal education, material culture is observed to be involved with story-telling, ceremonies, singing, and so on, stimulating the type of self-initiated sharing of attention also associated with hedonic pleasure and reward system activation (Schilbach et al., 2010).

Arrival of Numeracy and Literacy

Until the last few hundred years, reading, writing, and formal mathematics were acquired by only a small proportion of our population. This makes it unlikely that the genetically ingrained nature of our species has been influenced directly by the acquisition of these skills. Therefore, these new culturally acquired habits must build entirely on those cognitive abilities and neural circuits evolved to meet other purposes. This idea is expressed in the “cortical recycling hypothesis” (Dehaene & Cohen, 2011).

Material representations of number preceded other forms of writing by several thousands of years. When the Sumerians first settled to agrarian culture in the valley of the Tigris and Euphrates rivers around 8000 to 7500 BC, they left behind a variety of clay geometric shapes (cones, spheres, disks, cylinders, etc.) which are thought to have been used as tokens (Schmandt-Besserat, 1996). Material-based evidence of numeracy also precedes that of literacy elsewhere, such as use of the “khipu” in Caral (Peru)—identified as the first urban settlement in the Americas—and a region where writing arrived with the conquistadors almost 4,000 years later. From around 4.5 kya (Mann, 2005), the khipu is a knotted-string device thought to be used for bureaucratic recording and communication (Urton, 2011; Urton & Brezine, 2005). Given the economic trading complexities of settled existence, it may be unsurprising that written number preceded other types of writing. For example, urbanites at Caral thrived by growing cotton for the fishing nets of those living many miles away on the coast. Traders with access to a written record of quantity would have been greatly advantaged in the exchange of goods that the community depended on.

Just as human symbolic language had candidate precursors evident in other species, so we find a broad range of animals regularly use a primitive number-competence to make informed decisions (e.g., in foraging or in social interactions such as fights; Nieder & Dehaene, 2009). The existence of a primal numerical system is further evidenced by monkeys, as well as human adults and children, who exhibit similar intraparietal sulcus activation during analog numerical processing (Cantlon, 2012). Rather than simply occurring independently in time, it has been argued that the development of number is itself an important intermediate stage in the development of symbols for language. Schmandt-Besserat (1996) points to how clay tokens became obsolete by 3000 B.C. in Sumeria, replaced by pictographic tablets able to communicate not only “how many” but also “what, where, when, and how.” Tokens can become pictorial representations and, instead of reproducing them many times over for a single representation of a quantity, the use of a numeric symbol appears a straightforward progression. Moreover, that symbol might then be used to represent the same quantity of different types of objects, and later be combined with a symbol for the object. In this way, Schmandt-Besserat presents us with a

set of small incremental steps by which pictographic writing could develop into cuneiform notation, thought to be the world's first written language.

By the time an individual's brain comes into contact with reading, writing, and mathematics, some of the general-purpose plasticity of the cortex will already have been reduced by experience. Early in development, the most dominant environmental characteristics (such as object contours) interact with an individual's developing brain and these interactions are internalized in the development of cells, receptor densities, and connectivity patterns (Krubitzer & Seelke, 2012). The characteristics of symbols for numeracy and literacy encountered by a learner must, therefore, be accommodated within a brain partially molded by this early gene-environment interaction, via learning processes also subject to similar biological constraints. Thus, the recycling hypothesis predicts bidirectional influence and constraints between the brain and the medium of culture (Dehaene & Cohen, 2011). For example, reading acquisition recruits cortical regions possessing receptor fields able to recognize character shapes (the Visual Word Form Area or VWFA) with connections to those parts of the left temporal lobe used for language (Brem et al., 2010). Visual regions with such plasticity constraints are likely to have influenced the cultural development of written language, encouraging convergence onto a small set of symbol shapes that these regions can optimally learn. Since the VWFA evolved to serve object recognition, these constraints will derive from an individual's early interaction with the properties of natural objects. This helps explain why the world's writing and symbol systems tend to use the same set of line junctions, whose frequency profile matches that of natural scenes (Changizi, Zhang, Ye, & Shimojo 2006). The VWFA continues to be involved with other types of visual processing, including faces. Interestingly, a study of reading acquisition by illiterate adults showed this region decreased its sensitivity to faces as it acquired increased sensitivity to word (Dehaene et al., 2010). This suggests reading acquisition may involve regional competition with the processing of stimuli important for other types of communication, although any behavioral consequences of this competition are still to be investigated.

Writing expresses a symbolic system of communication suitable for the generation and expression of reasoning. While approximate arithmetic still exploits our primitive numerical abilities and recruits left/right parietal regions, formal mathematics recruits left-hemisphere language networks and is more intimately involved with language (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). Therefore, the interrelated nature of formal numeracy and literacy development extends after the prehistoric generation of component symbols, and a complimentary relationship between number and writing has been undoubtedly contributing to the cultural explosion during the last 10–20 thousand years.

IMPLICATIONS FOR EDUCATION

It Is Education That Makes *H. sapiens* Extraordinary

Present evidence suggests the neural advantage of our species is restricted to the absolute number of neurons in our brains, an advantage derived from being a scaled up version of other primates. Other extinct hominid species may have shared this benefit. We are not, therefore, “evolutionary outliers.”

Despite this lack of extraordinary biological difference, human behavior is undeniably extraordinary. However, there is little evidence to suggest our critical advantage was a special, genetically transmitted difference that has no precedent. On the basis that phenotype is a product of genes and environmental history, this lack of radical genetic difference places greater emphasis on the cumulative cultural evolution of our environment. Although this cultural transmission of knowledge began very slowly, with a pace controlled in large part by external influence, it eventually facilitated the transmission of new and efficient tools of cultural transmission, initiating a spiraling increase in information transfer between generations that became manifest as a cultural explosion. These tools of cultural transmission include social learning, social motivation, writing, reading, and teaching. Collectively, and in the broadest sense that includes all its informal manifestations, the tool set that has made our species extraordinary may be called education. It is education, then, that has transformed a large, if otherwise ordinary, member of the primate family into the most extraordinary species on our planet.

This may not be news to many teachers and policymakers who already consider education to be the most important enterprise and investment priority for human society. However, it could be argued that the “new thinking” in evolution may help imbue the political status of education with a fresh sense of importance and urgency. For the primary cause of our much-celebrated supremacy, we must now lose our inherited primacy and a belief that our abilities have been won through millennia of prehistoric evolution. Instead, we have something more ephemeral and vulnerable—a set of cultural practices requiring constant investment for their protection and growth.

Education appears as the most powerful and transformational set of tools that our species possesses but, like most tools, there are attendant dangers. For most of the 150 years since Darwin, it could be argued that education's transformative power has fooled us into thinking that our species must, in some ways, be more biologically special than those of others. That, perhaps, has been unhelpful in its affordance of a species-centric view of our universe. At the same time, our new perspective reminds us of the likely cultural basis for behavioral and cognitive differences between races within our species, and the powerful role of education in determining

these differences and the basis of who we are as individuals. This emphasizes the extent to which formal education, as a directed effort to influence cultural transfer and everything that our species boasts as special, has great political potency. For example, there is an inevitable tension between the need to update and protect the tool set. Policies that deprive indigenous peoples of an up-to-date education also deny them access to cultural tools required for their political empowerment. On the other hand, successful programs of education amongst indigenous peoples are characterized by a “bottom-up” approach that builds upon and strengthens, rather than displaces, the existing tools used to transfer cultural identity and indigenous knowledge across generations (Fogarty, 2012).

A Prehistoric Cultural-Genetic Lag Impinges on Constructions of Normality

Over just the last few thousand years, we have culturally inherited a massively changed environment and ever-more powerful means to transform it further. Our genetic basis, however, is less transformed and our interaction with this new world involves recycling our biology in new ways. This prompts reconsideration of the role of biology in learning difficulties such as dyslexia and dyscalculia, and the extent to which these should be considered as “abnormal” trajectories. In the past, there may have been gradients of genetic variation that were unproblematic or, more speculatively, occasionally advantageous until a generation was required to read and perform processes such as long division (Thomas, 2013). It may seem less surprising then, that a significant proportion of the population has difficulty with such recent and demanding changes in the environment. These new cultural demands require the association of sounds and number sense with written symbols in the early years of an individual’s development, requiring types of mental procedure and processes of cortical recycling for which we are unlikely to be optimally adapted.

While lack of selection for written literacy and numeracy can be argued on the basis of the population’s limited exposure, a cultural-genetic lag may reach further back in time than the advent of written symbols, and so be relevant to a broader range of mental processes. Oral and other cognitive abilities are likely to have been practised by a greater proportion of the population over a much larger period of time. They can be reasoned to have played an important role in an individual’s reproductive and survival success, yet evolution appears to have poorly promoted them. Children with specific language impairment (SLI) master language milestones much later than normal, and their use of syntax and vocabulary may be constrained by its simplicity into adulthood. As with other learning difficulties such as dyslexia and dyscalculia, there appears to be a strong genetic element, with studies revealing a high heritability

of the disorder (Bishop, 2002). Since the prevalence of SLI is estimated to be as much as 7% (Tomblin et al., 1997), an optimal genotype for oral communication appears not to have reached fixation in our species. A common explanation for a genetic allele being maintained by a population is that its disadvantageous traits may be counterbalanced by other, perhaps as yet unidentified, advantageous traits. One flaw with this idea, however, is that it requires a fairly exact balance in terms of reproductive and survival success between the allele’s positive and negative affordances (Keller & Miller, 2006). One might also, of course, consider that this is simply a case of “work in progress”—and perhaps human evolution is just progressing at a slower rate than some might expect. Yet there is little evidence that genetic variants are adaptively evolving and influencing cognitive abilities in this way (Bishop, 2009). A further explanation suggests our cognitive skills are subject to the combined effect of many genetic and environmental influences, with little variance in cognitive outcomes explained by individual alleles (Wright, Charlesworth, Rudan, Carothers, & Campbell, 2003). This combined effect can be associated with high heritability, but distribution of the many contributing alleles across the wider unaffected population would detract from the effectiveness of selection. Supporters of this multifactorial model point to the increasing numbers of genetic variants found to be related to learning difficulties whose individual effect is small and that occur widely amongst the “normal” population (Plomin, Kovas, & Haworth, 2007). The model is also supported by the observed influence of these variants on the skills of these “normal” learners, emphasizing the lack of any clear dividing lines between normality and abnormality (Plomin, 2008).

Education has Impacted on Our Biological Evolution, but Perhaps Only Indirectly

The importance of continuing genetic change in our species should not be discounted, and it would be wrong to present cultural and genetic change as explanations for the human story that are mutually exclusive. Small, but behaviorally significant changes in the genetic make-up of a species can occur over the space of a few years (Grant & Grant, 2006). While the tools of modern and sophisticated forms of literacy and numeracy have, until recently, been available only to a small percentage of the human population, small advances in symbolism (such as counting for trade) can become responsible for significant changes in lifestyle, such as diet. Such changes have brought about genetic changes in a population. The development of dairy farming in Europe, for example, is thought to have created selection pressures that favored the allele for lactose absorption in pastoral populations. A more ancient example may be the reduction in gut size in relation to the use of fire as a means to cook (Wrangham, 2001). However, since genetic innovations over

the last few thousand years appear mostly restricted to issues of diet and disease, ideas suggesting a strongly influential and direct role for education in our neurobiological evolution may need to be approached with caution. For example, evolutionary biologists have observed how organisms modify their environments (termed “niche construction”). They have considered how these niches may bring about evolutionary change by influencing selection, in addition to niches being the behavioral expression of modified phenotypes (Odling-Smee, Erwin, Palkovacs, Feldman, & Laland, 2013). It has recently been suggested that niche construction theory might be usefully applied in considering human construction of cultural niches (Flynn, Laland, Kendal, & Kendal, 2013). This may be helpful in exploring how an individual’s development is influenced by their own cultural niche, enriched by the cultural accumulation of generations of ancestral niche construction, in addition to their own construction efforts. It may also extend to indirect ways in which cultural transmission of knowledge becomes partially genetic, in the sense that construction of a cultural “dairy niche” can be passed down more meaningfully by those able to consume more dairy products. However, we have little evidence for a stronger form of this theory in which the cognitive processes encouraged by a cultural niche have more direct two-way influence with genes associated with their neural substrates. In addition, such a theory would predict some genetically-ingrained constraints on the neurobiological substrates of culture while instead we observe humans constructing a diversity of cultural environments. These observations include everyday instances of infants seamlessly adopting the language, customs and behaviors of their cultural environment, even when these would be alien to their most recent ancestors. We also see every culture boasting a variety of niches (in terms of multiple specialized roles) unlikely to be represented by different phenotypes. Rather than the evolution of cultural niches with a neurobiological basis, the complexity and fluidity of culture speaks of a general set of human abilities through which the learning processes and messages of culture can propagate (Thomas, 2013).

Neuroscience Can Help Us Understand Evolution—and Help Dissipate Evolutionary Neuromyths

Since Darwin, ideas about evolution have inspired influential ideas within education. Some of these ideas have merit, as well as flaws. The “new thinking” in evolution that draws on neuroscience may help identify the value as well the limits of these ideas. Triune brain theory drew attention to the evolutionary history of the brain but the foundational nature of our emotional and motivational systems is not well-represented by a model of competition between cortical and subcortical regions. EP, by emphasizing how an evolved bias in children’s learning and motivational systems should interest educators, suggests a psychological basis for educational

theory that draws on evolutionary concepts. However, cortical plasticity within an individual’s lifetime would have supported the type of domain-specific specializations that our Pleistocene ancestors required. Given the lack of evidence for genetically transmitted domain-specific modules being either necessary or possible, speculation that our Pleistocene habits still influence our learning behavior in school appears unfounded. In contrast, an evolutionary basis for modular bias in learning extends much further back in time. Most recently, niche construction theory has stimulated interesting discussions regarding the interrelation of evolutionary concepts with those popular in educational research (such as activity theory and situated learning), yet development of this theory may prove most relevant in respect of cultural, rather than genetic, transmission processes.

Evolutionary Perspectives May Help Identify How Neuroscience Can Inform Education

From an evolutionary perspective informed by neuroscience, valuable insight regarding behavioral bias can derive from considering the neurochemical processes we share with other animals and which evolved over deep evolutionary time. Motivational and emotional systems interact bidirectionally with the functioning of our more general-purpose plastic cortex. Critical consideration of this interaction can provide insight into the learning processes that guided us in the past and still influence us today, offering fresh insight into the frequently critical role of affect and motivation in classroom learning. For example, even when learning software was generated with expert understanding of cortical number sense processes, it was noted that the emotional response of the children to the format of training had the potential to limit its effectiveness (Wilson et al., 2006). At the same time, implicit appreciation of the foundational nature of motivational and emotional response is, perhaps, demonstrated by the increasing number of cognitive training programs that attempt to embed training algorithms in a game context (Jaeggi, Buschkuhl, Jonides, & Shah, 2011; Kucian et al., 2011). Elsewhere, neurocognitive understanding of the emotional and motivation response to games and learning games is now receiving more explicit treatment (Bavelier, Levi, Li, Dan, & Hensch, 2010; Howard-Jones, Demetriou, Bogacz, Yoo, & Leonards, 2011).

The interrelation of evolutionary concepts with other fields within and beyond science has always evoked strong debate. However, consideration of the “new thinking” in evolution has much to offer discussions interrelating mind, brain, and education. It can help scrutinize and dissipate myth, prompt a helpful reconsideration of the cultural and political status of education, offer fresh insight into our understanding of difference, and help encourage more appropriate emphasis on

the emotional and motivational processes that are foundational for learning.

NOTE

1 Note this is significantly less than the 100 billion figure frequently promoted elsewhere, whose origins appear somewhat mythical.

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