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Innovation in the Collective Brain

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Summary

Innovation is often assumed to be the work of a talented few, whose products are passed on to the masses. Here we argue that innovations are instead an emergent property of our species' cultural learning abilities, applied within our societies and social networks. Our societies and social networks act as *collective brains*. We outline how many human brains, which evolved primarily for the acquisition of culture, together beget a collective brain. Within these collective brains, the three main sources of innovation are serendipity, recombination, and incremental improvement. We argue that rates of innovation are heavily influenced by (1) sociality, (2) transmission fidelity and (3) cultural variance. We discuss some of the forces that affect these factors. These factors can also shape each other. For example, we provide preliminary evidence that transmission efficiency is affected by sociality—languages with more speakers are more efficient. We argue that collective brains can make each of their constituent cultural brains more innovative. This perspective sheds light on traits, such as IQ, that have been implicated in innovation. A collective brain perspective can help us understand otherwise puzzling findings in the IQ literature, including group differences, heritability differences, and the dramatic increase in IQ test scores over time.

Keywords: innovation, technology, cultural evolution, social learning, language, intelligence

INTRODUCTION

Sixty thousand years ago, a group of tropical primates left Africa and began exploring the world. By around 12,000 years ago, most of the planet's major ecosystems had been colonized—from lush rainforests to frozen tundra to arid deserts. The colonization of these diverse environments was achieved largely through culturally-evolved technological and social innovation, rather than through local genetic adaptation [although there was some of this too; e.g., 1]. Where did this technology and culture come from? How did our ancestors invent tools, discover knowledge, and develop a body of beliefs, values, and practices that allowed them to survive in environments so alien to their ancestral African homeland? And how can answering these questions inform our understanding of innovation through history and in the modern world?

A folk-historical answer to these questions is that smart people from days gone by invented these tools, discovered this knowledge, and prescribed and proscribed obligations and taboos. These practices and know-how were then passed down from generation to generation [2, 3]. Fire-making know-how, for example, is said to have been given to the Australian Aboriginals by Crow [4], to the Indians by Mātariśvan [5], and to the Greeks by Prometheus [6]. *Mimi* taught Australian Aboriginals to hunt and cook kangaroo [7], and more recently Shaka Zulu invented the *iklwa* short spear [8]. These savvy ancestors, who sometimes ascend to divine status, are often invoked to sanction proper form, protocols, or practices [9], reinforcing their "inventor" status. Non-WEIRD people [10] and members of small-scale societies are not alone in these beliefs. WEIRD children are taught that Edison (or Swan) invented the lightbulb, Gutenberg the printing press, Newton "the calculus", and Ford the automobile. The underlying intuition is that innovation is an individual endeavor, driven by heroic geniuses and then passed on to the masses. Or as Pinker [11] describes it, innovations (or "complex memes" [11]) arise when "some person knuckles down, racks his brain, musters his ingenuity, and composes or writes or paints or invents something" (p. 209).

We instead argue that innovations, large or small, do not require heroic geniuses any more than your thoughts hinge on a particular neuron. Rather, just as thoughts are an emergent property of neurons firing in our neural networks, innovations arise as an emergent consequence of our species' psychology applied within our societies and social networks. Our societies and social networks act as *collective brains*. Individuals connected in collective brains, selectively transmitting and learning information, often well outside their conscious awareness, can produce complex designs without the need for a designer—just as natural selection does in genetic evolution. The processes of cumulative cultural evolution result in technologies and techniques that no single individual could recreate in their lifetime, and do not require its beneficiaries to understand how and why they work [12; SM for further discussion]. Such cultural adaptations appear functionally well designed to meet local problems, yet they lack a designer.

Here, we outline in more detail the origins and machinations of collective brains. We begin by discussing the "neurons" of the collective brain, individuals with brains evolved for, and entirely dependent on, the acquisition of culture—*cultural brains*. Our cultural brains evolved in tandem with our collective brains, and are rather limited in isolation. Indeed, there are numerous examples of the failure of big-brained explorers to survive in new environments without access to cumulative bodies of cultural know-how [12]. We summarize the evolution of cultural brains and the resulting psychology, and then explain how such individual brains beget collective brains. We sketch how cultural brains are linked into collective brains that generate inventions and diffuse innovations, and then discuss factors that have influenced innovation rates throughout history and across societies. Heuristically, these can be partitioned into: (1) sociality, (2) transmission fidelity, and (3) transmission variance. Each of these factors influences the speed of adaptive cultural evolution and the rate of innovation, but they also affect each other. For example, cultural evolution may shape the transmission efficiency of languages. Illustrating this possibility, we show how the size of the community of speakers relates to the communicative efficiency of a language. These results suggest that language may be subject to the same cultural evolutionary processes as other technologies. Finally, we examine some of the ways in which collective brains can feedback to make each of their constituent cultural brains "smarter"—or at least cognitively better equipped to deal with local challenges. And in doing so, we address an understudied aspect of cultural evolution, how culture affects culture; that is, how ideas interact to change the innovation landscape, constraining and opening new *thought spaces*.

THE CULTURAL BRAIN AND THE COLLECTIVE BRAIN

Why are humans so different to all other animals? Many have suggested that the answer lies in our massive brains, which tripled in size in the last few million years [13, 14] and are 3.5 times as large as modern chimpanzees'. This increase is puzzling. And more puzzling still, it may be part of a longer-term trend toward larger, more complex brains in many taxa [14-16]. The source of the puzzle is that while both cross-species [17-20] and direct experimental evidence [21] suggest that larger brains are associated with greater cognitive ability, brain tissue is energetically and developmentally expensive [22]. A species needs to be able to pay for a larger brain. One way to lower the cost is by trading off other costly tissue, metabolic rate, and/or changing reproductive investment strategy [23, 24]. Another is to increase energy input by ensuring a reliable source of more calories [24]. To pay for our larger brains, we gained access to higher calorie foods—which we acquired through a combination of better tools and techniques for hunting; better know-how to access high-calorie food sources such as tubers, roots, and honey; and better food processing techniques [for a recent review and evidence, see 12]. In particular, processing food by cooking allowed our genus to unlock more calories from the same food sources, yet, as many college students can attest, cooking is not a reliably developing, genetically-hardwired skill. Our reliance on tools, techniques, and know-how that are not hardwired is a clue to solving the puzzle of the large human brain.

THE EVOLUTION OF CULTURAL BRAINS

Humans possess cultural brains—brains that evolved primarily for the acquisition of adaptive knowledge. A large body of theoretical and empirical evidence under the umbrella of *Dual Inheritance Theory* or *Gene-Culture Coevolution* now supports this perspective [for a recent review, see 12, 25, 26]. This *Cultural Brain Hypothesis* proposes that the primary selection pressure for large brains across many taxa was adaptive knowledge—locally adaptive information plausibly related to solving problems such as finding and processing food, avoiding predators, making tools, and locating water. The availability of this knowledge and the payoffs associated with it are what constrain the size of brains.

To explore the Cultural Brain Hypothesis, we recently constructed an evolutionary simulation model that captures the causal relationships outlined in Figure 1 (under review). Here we present a verbal exposition of this model. Brain size/complexity/organization (different measures of brain size are typically highly correlated [27]) coevolves with adaptive knowledge; larger, more complex brains can store and manage more information and in turn, this information can support the costs of a larger brain. This adaptive knowledge could be acquired asocially, such as finding a food source and remembering its location, or socially, such as copying a conspecific in a method of food extraction. More and better adaptive knowledge supports a larger carrying capacity by allowing more individuals to survive. And if those groups have enough adaptive knowledge, social learning might be favored. Social learners can acquire more adaptive knowledge at a lower cost, and without having to generate the information, do so with a smaller brain. Larger groups of social learners with more adaptive knowledge, create a selection pressure for an extended juvenile period to acquire this knowledge. And under some circumstances, this can lead to oblique learning and selective biases to distinguish who to learn from—the human pathway to truly cultural brains.

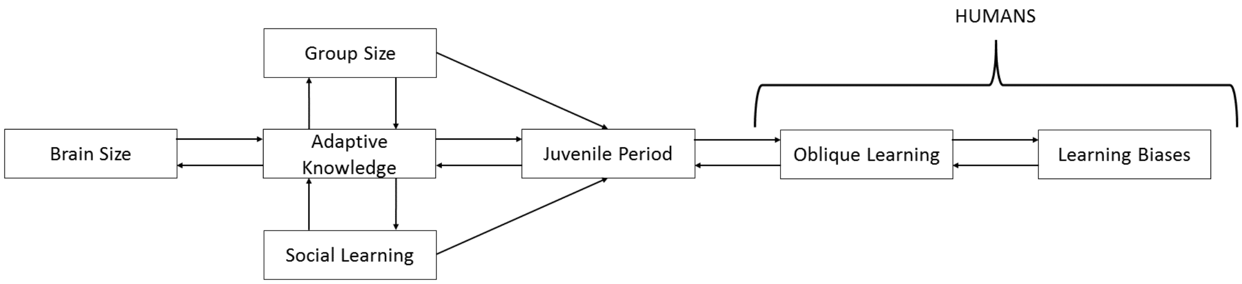

Figure 1. Causal relationships suggested by the Cultural Brain Hypothesis and captured in our simulation. Oblique learning and learning biases refer to the ability to select non-genetic parents with more adaptive knowledge from whom to socially learn.

Our simulation points to the existence of at least 2 regimes: species that rely more on asocial learning and species that rely more on social learning. In both regimes, the theory predicts a relationship between brain size and adaptive knowledge. For primarily asocial learners, the theory predicts a weaker (or non-existent) relationship between brain size/cognitive capacity and group size, since group size is only increased by increased carrying capacity through the benefits of adaptive knowledge. In contrast, for taxa with some amount of social learning, the theory predicts a strong relationship between brain size and group size (and other measures of sociality), since group size also provides access to more adaptive knowledge. In these taxa more reliant on social learning, the theory also predicts positive intercorrelations between the other variables in Figure 1.

The pattern revealed in our simulation are consistent with several lines of empirical evidence and also make further predictions that have yet to be tested. The theory is consistent with positive correlations between:

(1) Brain size and general cognitive ability [19, 20, 28]. Greater cognitive ability implies an increased ability to store, manage, integrate, and utilize more knowledge.

(2) Brain size and group size or other measures of sociality—the basis for the Social Brain Hypothesis [29]. Such relationships are a byproduct of brains evolving to acquire adaptive knowledge, and are predicted to be strongest among taxa with more social learning, since larger groups possess more adaptive knowledge for social learners to exploit.

(3) Brain size and social learning [18, 30]. More social learning evolves in the presence of more adaptive knowledge, allowing for larger brains.

(4) Brain size and the length of the juvenile period [31]. The juvenile period extends when social learners require more time to acquire a larger body of adaptive knowledge.

(5) Group size and the length of the juvenile period [32]. A byproduct of larger groups possessing more adaptive knowledge, which resulted in an extended juvenile period.

(6) Group size and number of cultural traits [33, 34]. Larger groups of social learners possess more adaptive knowledge. This relationship is expected to be strongest in the realm of cumulative cultural evolution [35-39]—humans.

These variables are interrelated, because they are a byproduct of brains evolving to acquire, store, and manage adaptive knowledge. The specific evolutionary pathway taken by different species is influenced by ecological and phylogenetic constraints related to the richness of the ecology (which affects payoffs for adaptive knowledge), mating structure and reproductive skew, the effectiveness of individual learning, and transmission fidelity. In our simulation, a narrow set of conditions lead to cumulative culture, a third regime of heavy reliance on social learning unique to humans. These conditions can be considered a *Cumulative Cultural Brain Hypothesis*.

The *Cumulative* Cultural Brain Hypothesis posits that the same processes that led to widespread social learning can, under some conditions, lead to an autocatalytic take off in brain size/complexity—the human pathway. Some of the conditions and prerequisites for this takeoff are as follows:

(1) **High transmission fidelity.** As with other models [e.g., 40, 41], our simulation suggests that high transmission fidelity is crucial for cumulative cultural evolution. Transmission fidelity is affected by many factors, including task difficulty (easier tasks are more easily transmitted); cognitive abilities, such as an ability to simulate other minds [Theory of Mind; 42]; proclivities, such as overimitation [43, 44]; social factors such as tolerance and pro-sociality [45, 46]; and culturally evolved innovations, such as teaching [47, 48].

(2) **Smart ancestors.** Entering this regime of genetic evolution driven by cumulative cultural evolution is more likely when the process begins with ancestors who are good at individual learning. These asocial learners developed a body of knowledge worth exploiting through social learning. Since not all individuals possess equally adaptive knowledge in a single generation, this can lead to oblique learning to learn from non-parents and learning biases to select the individual with the most adaptive knowledge. And of course having access to more potential models leads to a higher probability of acquiring higher quality knowledge. For further discussion, see SM.

(3) **Sociality.** Our model corroborates previous models in revealing a causal relationship between sociality and cultural complexity. This relationship is now supported by several independent experiments and convergent field evidence [reviewed in 12, 35]. Larger and more interconnected populations generate more, and more rapid, cumulative cultural evolution.

(4) **Mating structure, low reproductive skew.** Our model suggest that that low reproductive skew, consistent with "monogamish" mating structures, are more likely to lead to social learning and therefore to cumulative cultural evolution. Several researchers have posited the existence of ancient cooperative breeding human societies [reviewed in 49] and pair-bonding [12, 50], with evidence of both in among modern hunter-gatherers [51].

This approach proposes that human brains have evolved with an ability and proclivity for selective, high fidelity social learning. In a world of imperfect cues for the adaptive value of culture, there are a variety of strategies and biases that have evolved to hone in on the most adaptive knowledge. These strategies and biases include direct and indirect cues of the popularity of cultural traits [e.g., conformist transmission bias; 52], direct and indirect cues that a potential model has adaptive know-how worth learning [e.g., success and prestige biases; 35, 53], filtering mechanisms to assess the accuracy of information and sincerity of models [e.g., Credibility Enhancing Displays (CREDs); 54], personal relevance of culture [55], and biases toward certain content (e.g., dangerous animals [56], the edibility of plants [57], fire [58], and gossip [59]). For further discussion and reviews see [25]. These learning strategies selectively network many cultural brains into larger collective brains.

Networking Cultural Brains into Collective Brains

Underlying the many social structures of the collective brain is a psychology that supports both social norms and ethnic identification. Norms are the shared behavioral standards of a group and humans have evolved a suite of *norm-psychology* to infer and remember what these norms are; when, where, and to whom they apply (e.g., a norm governing women's use of menstrual huts); as well as how they are enforced; and the consequences and reparations for violations [46]. To understand to whom norms apply, we need to be able to identify group membership. Our species has an evolved *ethnic-psychology* to recognize and identify ingroups and outgroups—often overlapping (e.g., Spanish and Catholic) or embedded (e.g., American and New Yorker)—to which individuals belong and whom particular sets of norms may apply. Our ethnic psychology may have evolved from an earlier kin identification psychology, but in humans, ethnicities are often delineated by arbitrary markers allowing individuals to preferentially interact with those who share their norms [60]. In the presence of inter-group competition, our ethnic psychology can lead to ingroup favoritism [61]. Our ethnic-psychology and norm-psychology together tell us what groups we belong to and the expected behavior within those groups.

Once norm-psychology and ethnic-psychology evolved, the processes of cultural evolution could select for adaptive norms that support institutions and other social structures that solve adaptive problems. Marriage is a good example [for more discussion on marriage and other institutions, see 12: Chapter 9]. Marriage norms, in addition to alleviating problems of paternal uncertainty (by reducing infidelity), can bind larger groups of people in affinal (in-law) relationships with corresponding norms governing expectations and responsibilities [12: Chapter 9, 62]. Thus, from norms concerning marriage and family, cultural evolution can create norms concerning extended kin and kinship, leading to communities and other social structures of the collective brain.

The most basic structure of the collective brain is the family. Young cultural learners first gain access to their parents, and possibly a range of alloparents (aunts, grandfathers, etc.). Families are embedded in larger groups, which may take many forms, from egalitarian hunter-gatherers to villages, clans, and Big Man societies, from chiefdoms to states with different degrees of democracy, free-markets, and welfare systems, to large unions like the United States and European Union [for a discussion of the evolution of human societies, see 63, 64]. Social norms governing kinship can affect the degree to which these smaller groups integrate into larger groups. For example, more outgroup marriage (exogamy) can bind former clans into networks of related clans, traditionally called a tribe or ethnolinguistic group. Other cultural groupings include friendships and cliques, religious groups, formal institutions, castes, guilds and occupational specialization. These groupings have corresponding norms and specialized knowledge, and individuals may belong to multiple groups. Over time, the norms and regulations within these groups and institutions can be formally documented through legal codes and constitutions, creating more persistent, "hardened" norms. Thus, like the neural networks of the biological brain, the social networks of the collective brain have underlying structures.

Collective brains differ in many ways: size, interconnectivity, network properties, social groupings, and so on. And, as cross-cultural research reveals, collective brains also differ in the psychology of their constituent cultural brains. For example, some societies have a higher level of xenophobia [65] with potential implications for the inflow of ideas from outgroups. Societies also differ in "tightness" and "looseness" [66]—their openness to divergent ideas—with consequent effects for cultural variance [67]. In the next section, we discuss how innovations arise and diffuse, as well as the factors that affect the rate of innovation. We then discuss how these same factors change the cultural brain.

INNOVATION IN THE COLLECTIVE BRAIN

There are many potential sources of new ideas and practices in the collective brain and selective, high fidelity social learning ensures that these innovations are transmitted both horizontally throughout the population and vertically/obliquely from generation to generation. In human populations, culture has accumulated over generations to the point where no human alive could recreate their world in a single lifetime. However, not only is human culture beyond individual invention, it also does not require its beneficiaries to understand why something works. And in some cases, such as washing hands after using a toilet or performing a ritual, it is perhaps better that individuals don't understand the underlying mechanism [12: Chapter 7]! These innovations diffuse through transmission and selection mechanisms, but the question still remains—where do these innovations come from?

As we discussed, a common perception of the source of innovation is Carlyle's [68] "Great Man"—the thinker, the genius, the great inventor—whose cognitive abilities so far exceed the rest of the population, they take us to new places through singular, Herculean mental effort. They may stand on the shoulders of the Greats of the past, but they see further because of their own individual insight; their own individual genius. In the next section, we argue that culture runs deep and that these individuals can be seen as products of collective brains; a nexus of previously isolated ideas. But first, we discuss a collective brain perspective on the main sources of innovation: serendipity, recombination, and incremental improvement.

Revolutionary innovations often rely on luck rather than systematic and fully intentional investigation—i.e., serendipity provides individual with a glimpse under nature's hood. Innovations don't need intentional invention or anyone "racking their brains"; innovations can arise through mistakes in asocial learning or through imperfect cultural transmission (mistakes when copying) [39, 69]. Although we know of no systematic effort to compare the role of serendipity in innovation, the number of major inventions and discoveries due to accidents is impressive. These include Teflon, Velcro, x-rays, penicillin, safety glass, microwave ovens, Post-It notes, vulcanized rubber, polyethylene, and artificial sweeteners [for more examples, see 70]. The classic serendipitous discovery was Alexander Fleming, who discovered penicillin after noticing that his colonies of staphylococci had been killed by a mold that had drifted in through an open window. Unlike his discovery, Fleming's *mode* of discovery was neither remarkable, nor unusual. The basis for microwave ovens was discovered when Percy Spencer noticed that radar microwaves had melted a chocolate bar in his pocket. The hard, vulcanized, rubber in tires was discovered when Charles Goodyear accidentally brought rubber into contact with a hot stove and noticed that instead of melting, it produced a more robust rubber. The list goes on, and without a systematic analysis, we are forced to speculate about the degree to which serendipity has driven innovation over time. In each of these cases, however, it is worth noting that the inventor also had a mind prepared to recognise the discovery embedded in chance observation. Goodyear capitalized on luck, but his prior exposure at the Roxbury India Rubber Company had made him aware of their rubber problems [71]. With the right cultural exposure, one person's mistake is another's serendipitous discovery.

Cultural recombination, where different elements of culture are recombined in new ways, gives the appearance of inborn genius, but is the opposite—new ideas are born at the social nexus where previously isolated ideas meet. Theoretical models have shown the way in which recombination can generate innovations [e.g. 41, 72]. In the historical record, controversy surrounds the attribution of many of the greatest scientific discoveries, because they were discovered by multiple people at roughly the same time. Prominent examples include the theory of evolution by natural selection by both Darwin and Wallace, oxygen by Scheele, Priestley, and Lavoisier, and calculus by both Newton and Leibniz. Although theory predicts that recombination is crucial to innovation and we see recombination driving innovation in laboratory experiments [35], in the absence of systematic analyses of a random set of innovations, we are forced again to rely on case studies. The instances we mentioned represent a few instances of hundreds [73]. When we look across all of time, it may seem remarkable that these discoveries and inventions emerged so close in time, but this is consistent with *innovation as recombination*. Potential innovators, exposed to the same cultural elements arrive upon the same discoveries, in their own minds, independently; but from the perspective of the collective brain, these ideas are spreading and will eventually meet, unless they are forgotten first.

Both co-discoverers of the principle of natural selection had read Thomas Malthus' essays and Robert Chambers' *Vestiges of the Natural History of Creation*, and both had travelled extensively among diverse islands across archipelgos [74]. In most cases, we lack the appropriate data to track the shared cultural elements that led to each discovery.

There are many examples where "new" inventions are more clearly the product of incremental improvements, recombinations of existing elements, and selection; the "inventor" is really just the popularizer [which also speaks to our need to identify the responsible Great Man; 68] [1]. These "inventors" stand on a mountain of similar inventions. For example, although Edison and Swan are often credited with inventing the lightbulb, there were at least 22 inventors of incandescent lightbulbs prior to Ediswan's modifications and commercial success [75]. Similarly, though Gutenberg made some improvements to the printing press, his real contribution was in popularizing techniques and technologies available at the time [76]. Other world-changing inventions, including the steam engine [77], automobile [78], telephone [79], and airplane [80], were gradual improvements and recombination of previous advancements, complete with accidental discoveries and controversy over who came first. Again, we have relied on examples, and more quantitative efforts are needed.

Several other lines of evidence point to a crucial role of recombination, incremental improvement, and selection in innovation. One method that has proved useful has been the application of phylogenetic analyses to the constituent elements of a technology. These analyses, which have been applied to both portable radios [81] and bicycles [82], clearly reveal how the constituent components in a diversity of designs have recombined into the products we see today. Indirect support for the notion of innovation as the meeting of previously isolated ideas, practices, and understandings, comes from psychological data. For example, Maddux, Adam, and Galinsky [83] show that

[1] The prevalence of the belief in a Great Man or wise ancestor is itself an interesting phenomenon. This recurring theme may be grounded in our success-biases, seeking out successful and prestigious models from whom to learn, even if those models exist only in the past.

individuals with multicultural experiences are better able to connect seemingly disconnected concepts or words (e.g., "manners", "round", and "tennis" are connected by the word "table") and overcome functional fixedness (seeing an object's potential uses as limited to it traditional or designed uses) [83]. And finally, experimental evidence from a cultural transmission experiment show that when given access to multiple models, individuals selectively learn from the most successful, but also recombine knowledge from the next most successful models, leading to better outcomes than those who did not have access to many models [35].

At an individual-level, a collective brain perspective suggests that individual innovation benefits from exposure to a wide array of ideas, beliefs, values, mental models, and so on. This is part of what creates a "prepared mind". Einstein, for example, was exposed to many ideas working at a patent office. Much of his work related to evaluating patents on electrical devices, including those related to the synchronization of time, which made later appearances in his thought experiments. Einstein cultivated a wide network, regularly traveling and forming friendships with the leading scientists of his day [84]. At the level of the collective brain, there are many factors that affect the overall rate of innovation and diffusion. The rate of innovation has not been identical across societies [85] and appears to have been increasing in recent times [86, 87], as one would expect if innovation is being driven by recombination. Understanding the collective brain allows us to identify the factors that affect the rate of innovation.

Increasing Innovation Rates

Thus far we have outlined many of the processes that generate and transmit innovations within our collective brain. These can be distilled into an ontology that captures the factors that affect the rate of innovation. A useful starting point is an early model by Henrich [69] that attempted to explain the relationship between sociality and cultural complexity—why larger, more interconnected populations have more complex culture, and by corollary, why increases in sociality are associated with increased innovation. The logic is captured in Figure 2. The approach assumes that when a cultural model is chosen, based on cues linked to success or skill, most learners won't attain the level of skill (z_i) possessed by the model on-average; transmission is error prone and the bulk of the distribution is below the skill level of the chosen model. The graph, as shown in Figure 2, implies a relationship between the number of models individuals have access to and the mean complexity of culture that the population can maintain. Without delving into the maths, consider what would happen if we increased or decreased the number of accessible models. Assuming individuals always select the most skilled model, with access to more models, there is a higher probability of at least one model having a skill level in the right tail and a learner being able to select a model with *at least* skill z_i. Over several generations, there is an equilibrium skill value that can be maintained for access to a particular number of models (i.e., the number of individuals needed to consistently be able to access a model with skill value z_i). Thus, the first factor that affects the rate of innovation is *sociality*.

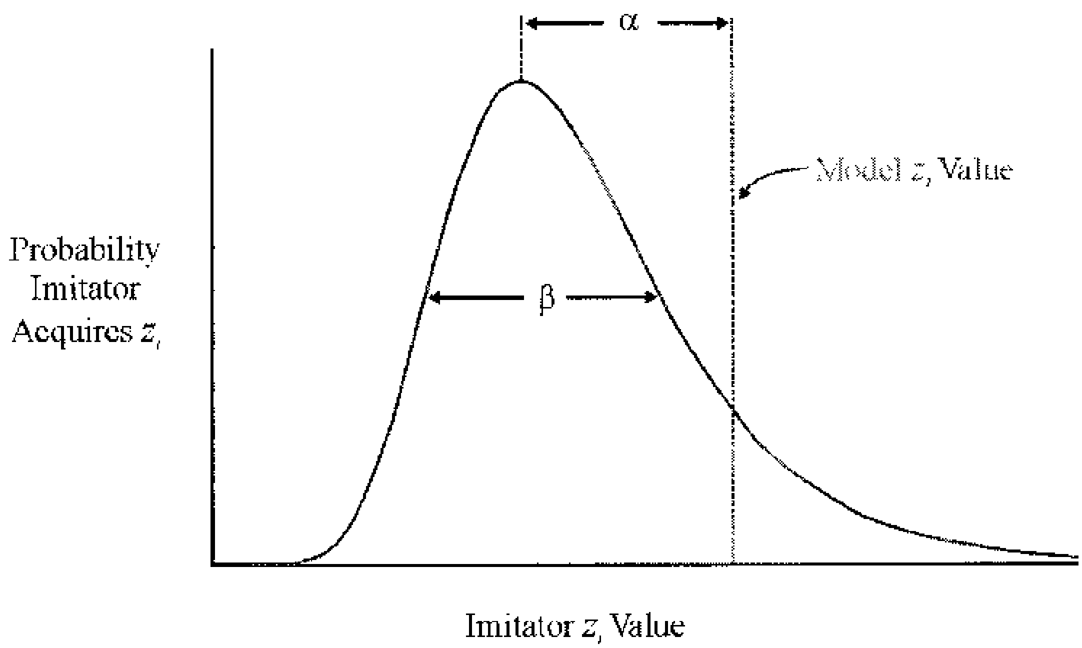

Figure 2. Gumbel probability distribution of imperfect transmission, reproduced from Henrich (2004). Analyses by Kobayashi and Aoki [88] confirm that this logic is not specific to Henrich's chosen distribution. For a given skill value z_i, the probability of acquiring a lower level skill (the portion of the distribution to the left of the dotted line) is less than the probability of acquiring an equal or greater skill level (the portion of the distribution to the right of the dotted line): learning is prone to error. As sociality and access to cultural models increases (e.g., through increased population size or density), there is a greater probability of at least one learner possessing skill level z_i or greater and becoming the most skilled cultural model from whom the next generation learns. These assumptions and logic predict a relationship between sociality and equilibrium cultural complexity.

The next factor we shall consider is the difference between the model skill and mean of learner skills, shown as α in Figure 2. The α parameter represents *transmission fidelity*. Higher transmission fidelity (lower α) increases mean cultural complexity. Finally, the β parameter represents the variance of the distribution—the variety of cultural inferences and outcomes. We shall refer to this as *transmission variance*. Higher transmission variance (higher β) can also increase mean cultural complexity (as well as the number of errors). There are many factors that increase and decrease sociality, transmission fidelity, and transmission variance, and in turn increase and decrease the level of innovation. Let us now consider a few.

There are several lines of evidence linking sociality to cultural complexity and innovation. For example, Kline and Boyd [33] show that both population size and island interconnectedness correlates with number of tools and tool complexity among Oceanic islands. Carlino, Chatterjee and Hunt [89] show that urban density (a proxy for interconnectivity) predicts the rate of innovation. Similarly, Bettencourt et al. [90] measure the relationship between the population of cities and number of new patents, number of inventors, and various measures of research and development. All scale exponentially, with a power law exponent greater than 1, suggesting accelerated gains as population size increases—exactly what one would expect if recombination is primarily responsible for innovation. These results are consistent with other archeological, ethnographic, and ethnohistorical evidence [see 35].

In the laboratory, three independent sets of experiments [35-37] tested the relationship between sociality and cultural complexity[2]. Together these experiments reveal that for sufficiently complex tasks, skill and know-how accumulate over generations when participants have access to more models and that while success-biased transmission is sufficient to drive the effect, where possible, participants also recombined information from multiple models. Muthukrishna, et al. [35] also tested the effect of loss of sociality by starting with a generation of experts. Confirming theoretical predictions, with access to fewer models, skill level reduced faster and reached a lower equilibrium.

With increases in population size and increases in interconnectivity thanks to literacy, radio, television, and most recently, the Internet, we should now be experiencing an unprecedented rate of innovation and adoption. Indeed, this is what we see. Analyses of the diffusion of technologies in 166 countries over the last 200 years suggest that adoption rates have been increasing [86]. Analyses of innovation within surgical techniques, as measured by patents and publications over the last 30 years, shows an exponential increase in innovations [87]. More research is required to understand what these staggering increases in sociality imply for the rate of innovation. To better understand the source of these relationships, future research should integrate (or recombine) the burgeoning body of research on social networks with cultural evolution. It is within these networks that individuals select cultural models and through these links that innovations are transmitted.

Transmission fidelity refers to the fidelity with which individuals can copy different ideas, beliefs, values, techniques, mental models, and practices. The factors that affect transmission fidelity relate

[2] Consistent with other innovations, these key experimental results emerged close in time [35, 36 were published online on the same day]—another case of simultaneous invention!

to all aspects of the transmission process, including the model, the learner, and the content being learned. Examples of factors that increase transmission fidelity include:

1. More social tolerance and prosociality—models that make themselves more accessible or are better teachers [47, 91, 92].
2. Access to more models demonstrating variations in practices and skills [35].
3. An extended juvenile period and/or longer lifespan, giving learners with more plastic brains more time to learn.
4. Better learning abilities, such as a better ability to represent and predict the mental states of others (better Theory of Mind).
5. Previously learned techniques and skills that make learning itself easier (e.g., mnemonics, study skills) or make new skills easier to acquire (e.g., discrete mathematics may make programming or game theory easier).
6. Finally, the content itself can simplify over time, with easier to remember steps or manufacturing techniques, thereby increasing transmission fidelity [93, 94]. The evolution of better modes of transmission, such as spoken language; more recently, written language; and more recently still, broadcast technologies such as the printing press, television, and the Internet, have also been a boon to transmission fidelity.

In Henrich's [95] model, transmission variance refers to the variance in inferences when copying skills, but the logic applies to cultural variance more generally. Just as with genetic mutations, more variance usually results in more deleterious mistakes (there are more ways to break something than to make it work), but as long as there are selection biases in who to learn from, the few serendipitous mistakes payoff for the population. There are many factors that affect transmission variation. These include (1) cross-cultural psychological differences in acceptance of deviance, tendency to deviate, and overconfidence and (2) institutional differences in policies that encourage and discourage deviation and risk taking. Research in the psychological sciences has identified cultural differences in "tightness" (strong social norms and low tolerance for deviant behavior) and "looseness" (weak social norms and high tolerance for deviant behavior) [96]. One measure of tightness and looseness is standard deviation in values and beliefs. Across 68 countries, a larger standard deviation is correlated with more innovation [67]. In contrast, more tightness is associated with more incremental rather than radical innovation [66]. A related cross-cultural difference is independence (or individualism) and interdependence (or collectivism), which may evolve for reasons that have little to do with innovation. Acemoglu, Akcigit, and Celik [97] focus on the quality or originality of innovations (e.g., number of citations per patent), rather than number of innovations. They find that individualism, lower uncertainty avoidance, and younger managers (all associated with higher variance), each lead to higher quality and more original innovations (also see [98]).

Economists typically assume material incentives drive innovators and thus innovations. However, from our point of view, recombination and incremental improvements are critical to innovation and patents can also stifle these processes by inhibiting the flow of information across individual minds, instead incentivizing secrecy. Consistent with this, historical analyses of patent laws by Moser [99] and recent analyses of human gene patents by Williams [100] both suggest that patent laws may often be too strong, reducing innovation, but this does not mean no patents would lead to more innovation. Based on data on pharmaceutical patents in 92 countries from 1978 to 1992, Qian [101] argues that there may be an optimal level of protection, after which innovation is stifled. Increasing innovation is about empowering the collective brain.

On the other end, reducing the costs of failure by creating a safety net can influence innovation via multiple channels, including by allowing individuals to invest in broader social ties (expanding the collective brain) over kin ties and by increasing entrepreneurship directly. This relationship is supported by analyses of England's Old Poor Law [102], more forgiving bankruptcy laws across 15 countries [103], unemployment insurance in France [104], and in the United States, the introduction of food stamps [105], health insurance for children [106] and access to health insurance unbundled from employment [107], all of which increased entrepreneurship. Of course, there's an optimal amount of social insurance vis-à-vis innovation, since increased funding of such programs can increase tax burdens—some data suggests that higher corporate taxes can lead to lower entrepreneurship [108, 109]. Overall, social safety nets energize innovation because they permit individuals to interconnect in broader, richer, networks.

Although we have discussed sociality, transmission fidelity, and transmission variance separately, they are interrelated. For example, sociality may have little effect if a task is too simple and therefore, transmission fidelity is very high [36] or individual learning dominates solutions. Similarly, theoretical and experimental research with social network structures [110-113] suggests that too much interconnectivity can decrease variance. The trade-off is between interconnectivity increasing the probability of useful recombinations in the incredibly high dimensional space of cultural combinations and the reductions in variance caused by our selective biases applying to large portions of the population. These results and the collective brain perspective suggest an optimal amount of interconnectivity. However, since real societal networks are far less dense than laboratory networks and we are far from a completely connected network, human society will probably continue to benefit from increases in interconnectivity (i.e., we are still on the positive slope). Moreover, variance is introduced by other factors, such as mistakes in transmission and individual differences in social learning and conformist biases (e.g., higher IQ individuals may be less conformist [52]).

Finally, the same principles that lead to larger populations possessing more complex technologies [e.g., 33] can also shape and hone the mechanisms of cultural transmission, such as pedagogy and language.

Various formal models have shown how cultural evolution may grow, hone, and optimize languages in a manner analogous to how cultural evolution shapes toolkits [12]. But unlike most tools, changes in languages can dramatically improve the efficiency of collective brains, just as myelination can make neural pathways more efficient over ontogeny. There are many ways that cultural evolution can optimize or make languages more useful. These include larger vocabularies [114, 115], bigger phonemic inventories, more grammatical tools [12], and more learnable syntactic morphologies [116]. Paralleling the relationship between population and toolkit size [33, 69], Bromham et al.'s [115] analysis of Polynesian languages reveals that as populations grow larger, they are more likely to gain new words and less likely to lose existing words. Indeed, the average American has a vocabulary approximately an order of magnitude larger than their counterpart in a small-scale society [114]. In the laboratory, just as manufacturing steps become more efficient in technological transmission experiments [93], artificial language transmission experiments reveal that over generations, these languages structurally change to become more learnable [117]. Paralleling this in the real world, Lupyan and Dale [116] show that languages with more speakers have an inflectional morphology more easily learned by adults, perhaps due to a greater number of adult second language speakers. However, increased learnability does not necessarily imply more efficient information transmission. Here, we push this line of thinking even farther to examine whether languages with larger speech communities have greater communicative efficiency.

One way in which languages can more efficiently transmit information is by optimizing word length by information content. That is, by shrinking words with less information and thereby increasing the correlation between word length and information content, the rate of information per unit time is more constant, resulting in "smoother" communication. Piantadosi, Tilly, and Gibson [118] measure this using Google's datasets of the 25,000 most frequently used strings for each of 11 European languages, calculating the information content for every word. Intuitively, information can be thought of as predictability, in this case the degree to which the word can be predicted based on the preceding context [119]. For example, in the sentence "When it rains I bring my ____", "umbrella" has far less information than "shotgun" since you could predict "umbrella" on the basis of the preceding words. Formally, Piantadosi et al. [118] estimate the average information content of a word $W = w$ in context $C = c$ using:

$$-\frac{1}{N}\sum_{i=1}^{N} log\, P(W = w|C = c_i)$$

where c_i is the ith occurrence of w and N is the frequency of w in the corpus. The context is operationalized using the N-gram model, in this case the 3 preceding words before w. Word length is defined as number of letters, which is highly correlated with both phonetic length and the time it takes to say the word. Piantadosi et al. [118] show that word length is strongly negatively correlated with information content—words with less information tend to be shorter, but that languages vary in the strength of this correlation. Here, we use those correlations to test if cultural evolution is shaping language as it does other cultural elements: Do languages with larger speech communities reveal greater optimization, as measured by the correlation between word length and information content.

The correlation between the log of number of speakers[3] (data from Ethnologue [120]) and the degree of optimization [118] is substantial: $r = 0.83$, $p = 0.002$, with a 95% confidence interval (bootstrapped) ranging from $r = 0.57$ to $r = 0.95$. Of course, these languages are related and therefore not statistically independent. To control for linguistic relatedness, we use the Indo-European language tree [from 121] to calculate independent contrasts for the log of number of speakers and degree of optimization using the *pic* function in the R package *ape* [122]. We then fit a linear model using these contrasts (leaving out the intercept term). The correlation between contrasts is $r = 0.77$, $p = 0.005$, with a 95% confidence interval (bootstrapped) ranging from $r = 0.50$ to $r = 0.91$. These preliminary results are consistent with a collective brain hypothesis, though we emphasize that much more extensive investigation is necessary (and these are currently underway).[4]

[3] The analytic relationship in Henrich [69] specifies a logarithmic relationship, so we use the log of number of speakers. A linear fit would imply a problem with the model. All data and code is available on the Dryad repository. doi:10.5061/dryad.k82pd.

[4] One potential alternative explanation for this relationship is that optimization is somehow driven by number of adult second language speakers or some other feature of contact with other languages. However, unlike learnability [116], it's not obvious how adult second language speakers could shorten words with less information. To the best of our knowledge, the number of second language speakers is only available for 4 of the 11 languages analyzed by Piantadosi et al. [118], so we are unable to eliminate this as a possible explanation.

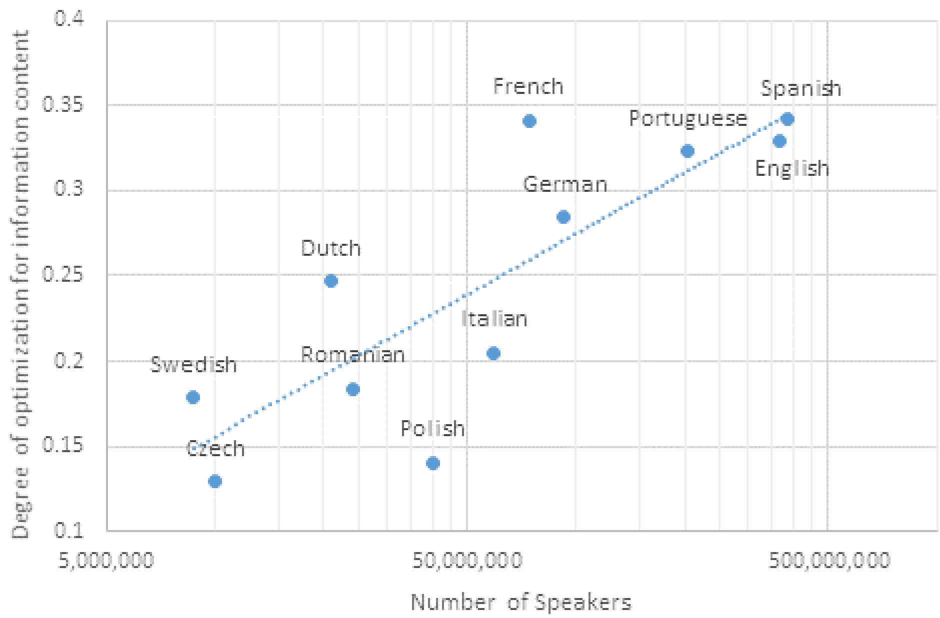

Figure 3. Relationship between the number of contemporary speakers of a language and the degree to which word lengths have been optimized for communication. The horizontal axis is a log scale. The vertical axis is the correlation between the information content of words and their written length made positive for easier interpretation.

In addition to language, cultural evolution may also be tuning the structures of the collective brain and the factors that affect sociality, transmission fidelity, and transmission variance. This tuning may offset a problem Mesoudi [123] discusses, whereby as cultural complexity increases, it is more difficult for each generation to acquire the growing and more complex body of adaptive knowledge. Consistent with this tuning, large-scale societies, with more complex technologies, engage in more teaching than small-scale societies [92, 124], thereby increasing transmission fidelity as cultural complexity increases. There is also some evidence for increases in division of labour (increased specialization), with more international trade and more domestic outsourcing of tasks (i.e., less vertical integration of all aspects of a business) [125, 126]. And despite these increases in pedagogy and specialization, our "extended juvenile period" has become further extended with delayed age of first child [127] and longer formal education [128]. Finally, Americans continue to expand their vocabularies across their adult lives, which has expanded the difference in the verbal IQs between adolescents and their parents relative to prior generations, where vocabularies expanded little after the mid-twenties.

In summary, sociality, transmission fidelity, and transmission variance all vary across populations and are subject to cultural evolution along a variety of dimensions. Over time, higher intergroup competition may favor institutions, such as social safety nets, that generate innovations. These factors affect the many ways in which innovations arise, such as exposure to more ideas (via cultural models prior to mass communication technologies), mistakes in transmission, and serendipity through fiddling around. If these processes are the primary mechanisms through which innovations arise, it would help explain the prevalence of Newton-Liebniz and Darwin-Wallace type controversies. Yet, in a population of millions, it was only Newton and Liebniz who discovered calculus, only Darwin and Wallace who developed the theory of evolution by natural selection; only a handful of people who actually invented each technology. Does the collective brain really relegate the specific innovator to a fungible node at a nexus in the social network? Do cognitive abilities, like IQ or executive function, really play no part?

THE COLLECTIVE BRAIN FUELS THE CULTURAL BRAIN

As we have discussed, innovations occur at the nexus where ideas meet. Thus, *ceteris paribus*, more innovations should occur in larger, more interconnected collective brains [33, 89, 90] and among individuals with access to more and diverse information [83]. But what about differences between cultural brains? Surely people differ in cognitive abilities and proclivities that affect their ability to innovate? Is the idea of innovation driven by big thinking geniuses truly untenable? In this section, we argue that collective brains make their constituent cultural brains more cognitively skilled in surviving in the local environment and better able to solve novel problems, using a larger repertoire of accumulated abilities. Intelligence is often assumed to underlie both individual and population differences in creativity and innovation [129-132, 133; for further discussion, see SM]. While in principle intelligence may increase transmission fidelity, intelligence (as measured by IQ) is only weakly correlated with innovativeness (as measured by creativity), $r = 0.20$, and is at best a necessary, but not sufficient condition for creativity [130]. Based on the arguments outlined in the previous section, we should expect that the collective brain can make cultural brains smarter through a combination of exposure to more ideas (sociality), better learning (transmission fidelity), and willingness to deviate (transmission variance). Of these 3 factors, exposure to more ideas is a necessary condition, since higher fidelity by itself would be associated only with incremental improvements and increased transmission variance by itself would be associated with more ideas, most of which would be bad. Consistent with this, multicultural individuals show more creativity [83], as do individuals with higher openness to new experience (but not the other Big 5 personality traits) [134]. Openness consistently predicted several measures of creativity, effect sizes ranging from $\beta = 0.25$ to $\beta = 0.66$, except math-science creativity, which may require more domain knowledge. Nevertheless, to illustrate our point about specialized psychological abilities, we'll address the common assumption that IQ leads to innovative ideas by showing how the collective brain can increase the IQ of cultural brains.

In a recent review, Nisbett et al. [135] suggest that there are still many unknowns and much controversy surrounding IQ data, let alone its interpretation. Based on Nisbett et al. [135], but avoiding interpretations and explanations, here are a few stylized facts regarding IQ (by "IQ" we mean whatever it is that IQ tests measure).

1. IQ is a good predictor of school and work performance, at least in WEIRD societies.

2. IQ differs in predictive power and is the least predictive of performance on tasks that demand low cognitive skill [jobs were classified based on "information processing", see 136].
3. IQ may be separable into crystallized and fluid intelligence. Crystalized intelligence refers to knowledge that is drawn on to solve problems and fluid intelligence refers to an ability to solve novel problems and to learn.
4. IQ appears to be heritable, but heritability scores may be weaker for low socioeconomic status (SES), at least in the United States.
5. Educational interventions can improve IQ, including fluid intelligence, which is affected by interventions, such as memory training.
6. IQ test scores have been dramatically increasing over time (Flynn effect) and this is largest for nations that have recently modernized. Large gains have been measured on the supposedly "culture-free" Raven's test, a test that measures fluid intelligence.
7. IQ differences have neural correlates.
8. Populations and ethnicities differ on IQ performance.

An understanding of cultural and collective brains allows us to make sense of these otherwise puzzling findings. Before we address each point, here is the broader, currently controversial claim: For a species so dependent on accumulated knowledge, not only is the idea of a "culture-free" IQ *test* meaningless, but so too is the idea of "culture-free" *IQ* [137]. Our smarts are substantially culturally acquired in ways that alter both our brains and biology, and cannot meaningfully be measured or understood independent of culture.

We argue that IQ is predictive of performance at school and work in WEIRD societies, because IQ measures the abilities that are useful at school and work in these societies. Culture runs deep and not only are obvious measures of cultural competence (e.g., verbal ability) a measure of culturally acquired abilities, but so too are less obvious measures, such as Raven's test. More thorough analyses are required to fully justify this perspective. Here we hope to inspire future work by laying out what this perspective implies for IQ alongside the evidence that does exist. The difference between crystalized and fluid intelligence is the difference between explicit knowledge and implicit styles of thinking, both of which vary across societies [138]. We will expand on this in the next section. For this reason, crystalized measures are more predictive of school performance than are fluid measures [139] and IQ is a weaker predictor of performance for jobs that do not require the skills measured by IQ tests. Moreover, we would predict that IQ tests would be less predictive of performance in locally valued domains in non-industrialized settings, such as many small-scale societies.

IQ measures appear to be heritable, but among lower SES, heritability is lower—though this finding is inconsistent. The collective brain would predict that IQ is most consistent from generation to generation when children have a similar probability of acquiring as much adaptive knowledge as their parents. This is highly variable, but most stable among those with high SES. In contrast, there is more variability (and therefore more potential predictors) among those with low SES. If exposure to knowledge affects IQ, then this is not surprising. Nor is it surprising that deliberate attempts to transmit information (formal education) improve IQ, as do deliberate attempts to improve thinking itself (such as memory techniques). These effects can be large.

Brinch and Galloway [140] measured the effect on IQ of a Norwegian education reform that increased compulsory schooling from 7 to 9 years. Their analyses of this natural experiment estimated an increase of 3.7 IQ points per additional year of education. Since this change only affected adolescent education, it is likely underestimating the overall effect of education on IQ. In another potential natural experiment, Davis [141] tested the IQ of the Tsimane, an indigenous forager-horticulturalist group in Bolivia. Some villages had formal schooling and others did not.

Children and adolescents with access to schooling showed a strong linear effect of age on IQ score ($R^2 = 0.519$), compared to no effect of age in those with no access to schooling ($R^2 = .008$). These results suggest that IQ increases with age not because of maturation, but because of the influences of a particular WEIRD cultural institution: formal schooling. This also suggests that through most of human history IQ did not increase with age. Moreover, it suggests a causal role of education in economic growth [see 142]. Although more evidence is needed to eliminate possible third variables, the evidence thus far is consistent with a collective brain hypothesis.

By our account, IQ is a measure of access to a population's stock of know-how, techniques, tools, tricks, and so on, that improve abilities, skills, and ways of thinking important to success in a WEIRD world. IQ tests are useful as a measure of cultural competence, which may require cultural learning (and there may be differences in this), but not as a universal test of "intelligence" as a generalized abstract problem solving ability. The Flynn effect [for recent meta-analyses, see 143, 144] describes the steady increase in mean IQ since IQ tests were developed, approximately 3 points per decade. If taken at face value, the Flynn effect renders large proportions of previous generations barely functional, but by this account, the Flynn effect becomes a measure of increased mean cultural complexity. This perspective is supported by data showing that IQ differences are strongly correlated with economic development [145]. Put another way, national IQ averages are exactly what one would expect if IQ were a measure of development; "one possible interpretation of the results… is that national IQ is just another indicator of development." (p. 95) Understanding the collective brain gives us the tools we need to understand the variation we see in the Flynn effect. Just as with other measures of cultural complexity and language efficiency, these differences should track changes in population size, interconnectivity, transmission fidelity (e.g., formal education), as well as the introduction of specific styles of thinking (e.g., analytic vs holistic).

Populations differ in IQ, also a cause of much controversy, and these differences correlate with various measures of economic and social development [129]. Although some [129, 131-133] have argued for a causal relationship between IQ and development, the theory and evidence we have laid out so far suggest the opposite causal direction. Sociality (the size and interconnectedness of a population) leads to increased cultural complexity. Increased cultural complexity in turn smartens cultural brains by giving them access to a wider array of information, including physical, cognitive and linguistic tools, which may be recombined in new ways, generating new innovations.

All of this is not to say that individual cognitive differences are unimportant to invention and innovation, only that these differences, like innovation, are an emergent property of the collective brain and that the focus on IQ, genius, and other individual differences, as the *source* of innovation have missed the broader collective brain processes that explain within-group and between-group differences. Within-populations, individual differences in genes, nutrition, and so on, may predict differences in cognitive ability, but these are difficult to disentangle from access to different models and access to different cultural elements. Overall, the collective brain hypothesis suggests that not only is it better to be social than have raw smarts, but smarts as they apply to success in your local environment, *require* you to be social. The broad structures of the collective brain affect the smarts of its constituent cultural brains. So too can the actual content being transmitted within the collective.

Culture Affects Culture: Constraining and Opening Thought Spaces

That aspects of culture ought to affect other aspects of culture is obvious and uncontroversial, at least at a population-level. For example, changes in the efficiency of language affect the rate at which information can be transmitted. Inventions such as the printing press, television, and the Internet and practices such as reading and formal education change the fidelity and reach of transmission.

More controversial arguments have been put forth about how some institutions can influence subsequent cultural evolution, such as monogamous marriage favoring lower fertility and greater gender equality [146]. What is less obvious is the ways in which cultural elements affect other cultural elements within individual brains. And less obvious still is how we might go about understanding these interactions.

Acquiring some skills and knowledge can make other skills and knowledge more obvious, natural, or easier to acquire—living in a country that drives on the left or right side of the road can affect whether it feels more natural to walk on the left or right side when passing people (leading to chaos at airports!). The importance of this can be thrown into stark relief by looking at our closest cousins. Gruber et al. [147] ran a novel honey extraction task with honey stored in logs with holes drilled in the side. Chimpanzees from communities with dipping stick technology spontaneously manufactured sticks to extract the honey. Those from communities without any dipping stick technology were unsuccessful. In a follow up study, Gruber et al. [148] tried to make it easier, leaving an already manufactured stick in the vicinity and even leaving it already placed in the hole. Even so, those from communities without the dipping stick technology ignored or even discarded the stick notwithstanding it already being placed in the hole!

Such studies of how exposure to previous ideas affect the creation of other ideas have not been performed with humans, at least not so deliberately, but in principle they are possible. These chimpanzee experiments also reveal that while exposure to previous ideas can open new thought spaces, they can also constrain thinking. If your collective brain only possesses hammers, everything looks like a hammer and all problems look like nails. But if the collective brain also has access to blades, hammers and blades may combine to open the space of axes with handles. We need not confine ourselves to hypotheticals. Educational psychology shows how learning some skills improves the acquisition of others. Exposure to Socratic questioning improves critical thinking more generally [149]; learning the method of loci (attaching items to a physical location in memory) improves performance on memory tests [150], and exposure to the history of Darwin's thought processes lead to a greater understanding of evolution [151]. These may seem obvious, but demonstrate how exposure to new techniques and ideas can affect the acquisition of other techniques and ideas. In other cases, the links between elements of culture are not so direct. Cross-cultural differences in analytic vs holistic thinking [152] have been argued to have implications for various other values, beliefs, and behaviors from the evaluation of brands [153] to the construction of built environments [154].

Ideas have interacted, recombined, and shaped each other throughout history and in doing so, they have opened up new thought spaces and constrained others. The invention of the wheel, invented long after agriculture and dense populations, occurred only in Eurasia. Its invention allowed for the invention of wheelbarrows, pulleys, and mills—all absent outside Eurasia. Similarly, the discovery of elastic-stored energy allowed for the invention of bows, spring traps, and string instruments—all absent in Australia, where elastic-stored energy was not invented. Compressed air allowed for blowguns, flutes, and horns, and ultimately bellows, metallurgy, and hydraulics.

The invention of these technologies also allows us to better understand the principles that underlie them—understanding the thermodynamics of a steam engine is a lot easier when you actually have a steam engine! [12] We use our technologies as metaphors, analogies, and concepts and they allow us to understand and innovate in ways we could not without such culture.

The way in which ideas have shaped each other is a neglected aspect of cultural evolution, because it can be difficult to study. Here we offer some paths forward. Experiments can reveal the ways in which specific techniques and knowledge affect the acquisition of other techniques and knowledge, and the field of educational psychology is a useful starting point. Cross-cultural comparisons can show how the presence or salience of some beliefs, values, and practices affect other beliefs, values, and practices. And the advent of large historical text corpora [e.g., Google N-grams; 155] and databases of history [e.g., 156] allows for systematic historical analyses of how the emergence of some ideas and technologies have allowed for the innovation of other ideas and technologies. Cultural phylogenetic analyses hold the potential to study how the evolution of one type of institution or practice influences the adoption of other institutions. Given the way in which ideas interact in the cultural brain and how the cultural brain accesses ideas in the collective brain, it should be clearer why culture and cognitive ability cannot be disentangled and why we might expect cross-cultural differences in cognitive abilities. Ultimately, further investigation of "culture-culture coevolution" may open the doors to a science of history. And in turn, as the mechanisms of the collective brain reveal, such investigation and recombination will lead to new innovations and new thought spaces.

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