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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' psychology, 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 the rate of innovation is primarily determined by (1) sociality, (2) transmission fidelity, and (3) transmission variance. There are many forces that affect each of these factors. By analyzing data from large corpora for 11 European languages, we show that sociality has shaped communicative efficiency—languages with more speakers are more efficient. Finally, we argue that collective brains can make each of their constituent cultural brains smarter. This perspective sheds light on otherwise puzzling findings in the IQ literature, including differences between groups, differences in heritability, and the dramatic increase in IQ test scores over time (Flynn effect).

**Keywords:** innovation, cultural evolution, social networks, 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]. An orphan boy taught the American Cree to hunt buffalo [7], the *Mimi* taught Australian Aboriginals to hunt and cook kangaroo [8], and more recently Shaka Zulu invented the *ikhwa* short spear [9]. These savvy ancestors, who sometimes ascend to divine status, are sometimes invoked to enforce proper form, protocols, or practices [10], reinforcing their “inventor” status. Non-WEIRD people and members of small scale societies are not alone in these beliefs. WEIRD children are taught that Edison (or Swan if you're British) invented the lightbulb, Gutenberg the printing press, and Ford the automobile; that Newton invented calculus, Priestley discovered oxygen, and Darwin developed the theory of natural selection. 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, big or small, don’t 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]. Such cultural adaptations appear functionally well designed to meet local problems, yet they lack a designer.

In this paper, 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 (see Henrich’s *Lost European Explorer Files* [12]). We summarize the evolution of cultural brains and the resulting psychology, and then explain how such brains beget a collective brain. We outline how cultural brains linked in a collective brain generate inventions and diffuse innovations. We then discuss the factors that have affected the rate of innovation across societies and through history. Heuristically, these can be organized into three interrelated factors: (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. To illustrate their interrelatedness, we analyze the complexity of different languages and show that languages with a larger number of speakers (higher sociality) are more efficient. Finally, we examine some of the ways in which collective brains can feedback to make each of their constituent cultural brains “smarter”. And in doing so, we address an understudied aspect of cultural evolution—culture-culture coevolution—how culture affects culture; 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 despite some evidence of recent shrinkage [15], 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, 17]. The source of the puzzle is that while both cross-species [18, 19] and direct experimental evidence [20] suggest that larger brains are associated with greater cognitive ability, brain tissue is energetically expensive [20]. 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 [21]. To pay for the calorie cost of our larger brains, we shrank our expensive gut tissue. But in order to do so, we required 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 an innate,

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, 22, 23]. Muthukrishna et. al. [24] formally model this and propose two related hypotheses: The Cultural Brain Hypothesis and the Cumulative Cultural Brain Hypothesis [for details of the argument and model, see 12, 25].

The 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. This proposal is consistent with Reader et al.’s analysis of 62 primate species, which suggests general intelligence in primates [26]. It is also consistent with analyses which suggest that brain size correlates with general cognitive ability [19, 27, 28]. Other relationships, such as the correlation between brain size and group size, the basis for the Social Brain Hypothesis [29], are a byproduct of brains evolving to acquire adaptive knowledge. The Cultural Brain Hypothesis predicts the existence of at least 2 regimes—species that rely mainly on asocial learning and species that rely mainly on social learning. The Cultural Brain Hypothesis makes several predictions about relationships between brain size, adaptive knowledge, group size, social learning, and the length of the juvenile period. The predictions that have been tested in the empirical literature support the hypothesis: In addition to the relationship between brain size and group size, these include positive relationships among social learners between brain size and social learning [28, 30], brain size and the length of the juvenile period [31], group size

and the length of the juvenile period [32], and group size and number of cultural traits [33, 34]. These variables are interrelated, because they are a byproduct of brains evolving to acquire, store, and manage adaptive knowledge.

The causal relationships predicted by the Cultural Brain Hypothesis are outlined in Figure 1 below. Brain size 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 larger groups. 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. Indeed the model predicts an initial shrinking of brain size during the transition to heavy reliance on social learning, before increasing again. Larger groups of social learners with more adaptive knowledge, create a selection pressure for a longer 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. The prerequisites and conditions that lead to cumulative culture are the predictions of the Cumulative Cultural Brain Hypothesis.

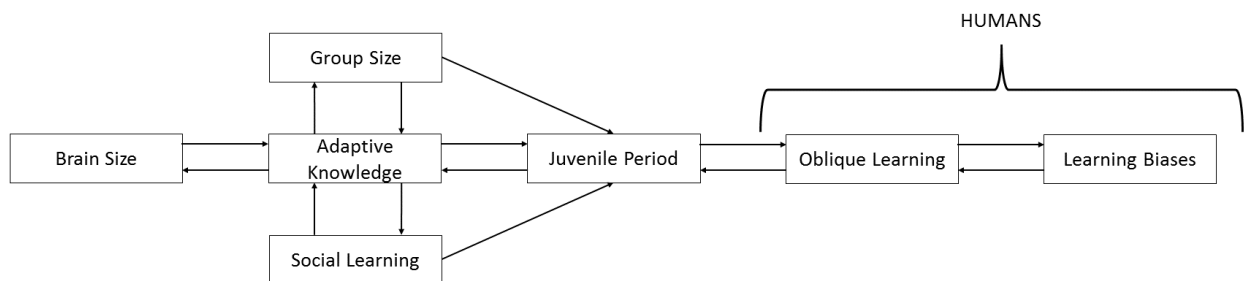


Figure 1. Causal relationships suggested by Cultural Brain Hypothesis.

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—the human pathway. This takeoff occurs under certain conditions and with certain prerequisites. These are as follows:

- (1) **High transmission fidelity.** As with other models [e.g. 35, 36], we predict that high transmission fidelity is a pre-requisite for culture to accumulate. Learning biases may be adaptive with social learning, but only high fidelity transmission allows culture to accumulate. Based on their review of laboratory studies, Claidière and Sperber [37] estimate human transmission fidelity at 86%. Humans are probably capable of at least 86% fidelity, but 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; 38]; proclivities, such as overimitation [39, 40]; social factors such as tolerance and pro-sociality [41, 42]; and culturally evolved innovations, such as teaching [43, 44]. However, Claidière’s and Sperber’s [37] analyses also reveals that other animals, such as Norway rats, are capable of transmission of up to 95% in particular domains such as food preferences. Norway rats don’t possess cumulative cultural evolution, thus transmission fidelity is necessary, but not sufficient for the evolution of cultural brains.
- (2) **Smart ancestors.** We argue that the uniquely rapid rate of innovation in our species is a result of cultural-brained social learners linked in collective brains, but over evolutionary time, our model suggests that social learners in these co-evolutionary trajectories need to stand on the shoulders of effective asocial or individual learners. These asocial learners developed a body of knowledge worth exploiting through social learning, creating the necessary selection pressure for social learning to evolve. Since not all individuals may 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.

- (3) **Sociality.** Our model corroborates the results of previous models that suggest a causal relationship between sociality and cultural complexity [45-47]. This relationship is now supported by several independent experiments [48-50]. Sociality gives oblique learners a greater range of models to apply their learning biases, which generates more rapid cumulative cultural evolution. The evolution of selectively-biased oblique learning strategies may have been helped by mating structures that gave learners easy access to more models.
- (4) **Mating structure, low reproductive skew.** Our model predicts that low reproductive skew, consistent with “monogamish” or cooperative 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 [51-56] with some evidence of cooperative breeding among modern hunter-gatherers [57]. Relatedly, other researchers have emphasized the importance of pair-bonding [12, 58]. The suggestion (which to our knowledge, has not been formalized) is that a young proto-human primate may have initially learned from mom as many chimpanzees do today [34, 59]. Mom may be the primary model simply because her children spend more time with her. Cooperative breeding and pair-bonding may have provided a young proto-human access to more moms, dads, and other relatives, opening a gateway to using selectively-biased social learning, where a young learner could focus on characteristics of the models, rather than how much access they had to them. These prerequisites are more likely to lead to cultural brains under certain ecological conditions. See Henrich [12: Chapter 17] for one scenario that links social learning, big brains, pair-bonding, kin identification, and alloparental care.



- (5) **Rich environments.** Our model suggest that richer ecologies can better support larger and therefore costlier brains. That is, when ecologies have a better return on adaptive knowledge, larger brains can evolve.

Our cultural 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; 60, 61-63], direct and indirect cues that a potential model has adaptive know-how worth learning [e.g. success and prestige biases; 48, 64, 65], filtering mechanisms to assess the accuracy of information and sincerity of models [e.g. Credibility Enhancing Displays (CREDs); 66, 67], personal relevance of culture [68, 69], and biases toward certain content (e.g. dangerous animals , the edibility of plants , fire , and gossip). For further discussion, see Chudek et.al. [22] and Hoppitt and Laland [70], and for a further list of such strategies and biases, see Rendell et al. [63]. The collective brain is made up of many cultural brains linked together, applying these strategies and biases.

## MANY CULTURAL BRAINS BEGET A COLLECTIVE BRAIN

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 during menstruation); as well as how they are enforced; and the consequences and reparations for violations. The evolution of norm-psychology is beyond the scope of this paper, but for a review, see [42]. 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. These groups are often delineated by arbitrary markers [71], which can lead to ingroup favoritism [72]. Very little is required to trigger our ethnic-psychology. Decades of *minimal group paradigm* research reveals that even arbitrary assignment to groups based on trivial categories such as art preference or tendency to overestimate is enough to trigger our ethnic psychology, with resulting ingroup favoritism and outgroup discrimination [73]. 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. Thus, from norms concerning marriage and family, cultural evolution can create norms concerning 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 genetic parents, and possibly a range of alloparents (aunts, uncle, grandma, grandpa, etc) in a cooperative breeding environment. Indeed, as discussed previously, a cooperative breeding structure may have been a critical step toward oblique learning and ultimately our suite of learning biases. These 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 74, 75]. Cutting across these groups are other

connections and groupings that influence and structure cultural evolution. These include the different sexes [for an example of sex-specific adaptive knowledge, see 76, for a potential origin of modern gender roles, see 77], friendships and cliques [for a review, see 78], internally and externally recognized ethnicities [71, 72] and religious groups [79], formal institutions, castes, guilds and occupational specialization [80]. These cultural 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.

The science of social networks is a relatively new area and more work is required to integrate it with psychology and cultural evolution. One question is how characteristic human network properties emerge. Muthukrishna and Schaller [81] show how differences in the tendency to connect with others combined with differences in physical proximity generate the properties commonly measured in human social networks. The connections created by cultural brains on the quest for the most adaptive knowledge can shape the social networks of the collective brain. A second question is what implications these network properties have. Pasquaretta, et al. [82] analyzed cross-species differences in the social networks of 78 groups of primates, representing 24 different species. Their analyses reveal more tolerant species, such as our own, had more egalitarian or distributed social network structures (low centralization) and were therefore, at least in principle, more efficient at transmitting information. Such a systematic comparative analysis has not been performed for other network properties, nor on the differences between human societies. The few cross-cultural analyses that have been performed have identified differences in sociality and structure [see 25, 81]—not all collective brains are equally capable of generating innovation.

Collective brains differ in many ways: size, interconnectivity, network properties, social groupings, and so on. And, as cross-cultural research reveals, they also differ in the psychology of their constituent cultural brains. For example, some societies have a higher level of xenophobia [83] with potential implications for the inflow of ideas from outgroups. Societies also differ in “tightness” and “looseness” [84]—their openness to divergent ideas—with consequent effects for cultural variance [85]. 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 innovation 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. But 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, performing a ritual, starting a business based on overconfidence, or other behavior that have benefits at a population-level, it is perhaps better that individuals don’t understand the underlying mechanism [12: Chapter 7]! These transmission and selection mechanisms ensure that innovations diffuse, 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 [86] “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. In the next section, we argue that culture runs deep and that these individuals can be seen as products of their 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.

When innovations are truly revolutionary, they are often the result of serendipity rather than systematic and fully intentional investigation—i.e. they are often accidental innovations that substantially improve upon the previous solution. At least in theory, accidental innovations can arise through mistakes when individually learning or through imperfect cultural transmission (mistakes when copying) [25, 45-47]. Although we know of no systematic effort to compare the role of serendipity to systematic scholarship in science and engineering, the number of major inventions and scientific discoveries due to accident 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 87]. The classic example of serendipitous discovery is Alexander Fleming, who discovered penicillin after noticing that his colonies of staphylococci had been killed by surrounding *Penicillium* mould, which inadvertently infected an experiment when a window was left open. Unlike his discovery, Fleming's *mode* of discovery was neither remarkable, nor unusual. Similarly, Teflon (Polytetrafluoroethylene) was discovered when Roy Plunkett noticed that his bottle of tetrafluoroethylene gas had dropped in pressure without a corresponding drop in weight. Upon examining the inside of the bottle, he discovered a very slippery coating. Likewise, the basis for microwave ovens was discovered when Percy Spencer noticed that radar microwaves had melted a chocolate bar in his pocket. Vulcanized rubber (the kind of hard rubber used in tires), was discovered when Charles Goodyear accidentally brought rubber into contact with a hot stove and noticed that instead of melting, it charred to produce a more robust rubber without the unwanted stickiness. The list goes on, but in each case, it is worth noting that the inventor also had a prepared mind capable of correctly recognizing the accident as a discovery. How many others may have dropped rubber into fire, but didn't recognize the charred remains as a useful new product? Goodyear's discovery was serendipitous, but of course prior cultural

exposure had also made him aware of the need for vulcanization. With the right 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 lone genius, but is the opposite—new ideas are born at the nexus where previously isolated ideas meet. Theoretical models have shown the way in which recombination can generate innovations [e.g. 36, 88]. In the historical record, controversy surrounds the attribution of many of the greatest scientific discoveries, because they were discovered by multiple people so close in 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. These are just a few cases out of hundreds [89]. When we look across all of time, it may seem remarkable that many of 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, as nexus of ideas. In the case of Darwin and Wallace (co-discoverers of the principle of natural selection), for example, this included reading Thomas Malthus' essays and Robert Chambers' *Vestiges of the Natural History of Creation*, as well as extensive global travel among diverse islands [90]. In other cases, we lack the appropriate data to track the shared cultural elements led to each discovery, but in many cases, “new” inventions are more clearly incremental improvements and recombination of existing elements and the “inventor” is really just the popularizer [which speaks to our need to identify the responsible Great Man; 86]<sup>1</sup>.

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<sup>1</sup> 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.

There are many examples where the “inventor” is really the popularizer, after several iterations of incremental changes and selection. 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 Edison’s modifications and commercial success [91]. Similarly, though Gutenberg made some improvements to the printing press, his real contribution was in popularizing techniques and technologies available at the time [92]. Other world-changing inventions, including the steam engine [93], automobile [94], telephone [95], and airplane [96], were gradual improvements and recombination of previous advancements, complete with accidental discoveries and controversy over who came first.

Several lines of evidence support the role of recombination, incremental improvement, and selection in innovation. Applying phylogenetic analyses to the constituent elements of a technology have proved useful. These analyses, which have been applied to both portable radios [97] and bicycles [98], break down each technology into its constituent parts and show how these parts have recombined into the products we see today. Further support for the notion of innovation as the meeting of previously isolated ideas, practices, and understandings, comes from psychological data, which shows that individuals with multicultural experiences are more creative [99]. 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 [48].

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. Einstein, for example, whose name is now synonymous with “genius” 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 developed a wide network, regularly traveling and cultivating friendships with the leading scientists and mathematicians of his day. [100] 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 [101] and appears to have been increasing in recent times [102, 103], 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 theory by Henrich [45] that attempted to explain the relationship between sociality and cultural complexity—why larger, more interconnected populations have more complex culture. The logic of the theory is captured in Figure 2. The theory assumes that when a cultural model is chosen (based on some direct or indirect cue of success or skill), on average most learners won't attain the level of skill ( $z_i$ ) possessed by the model; 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. consistently being able to access a model with skill value  $z_i$ ). Thus, the first factor that affects the rate of innovation is *sociality*.

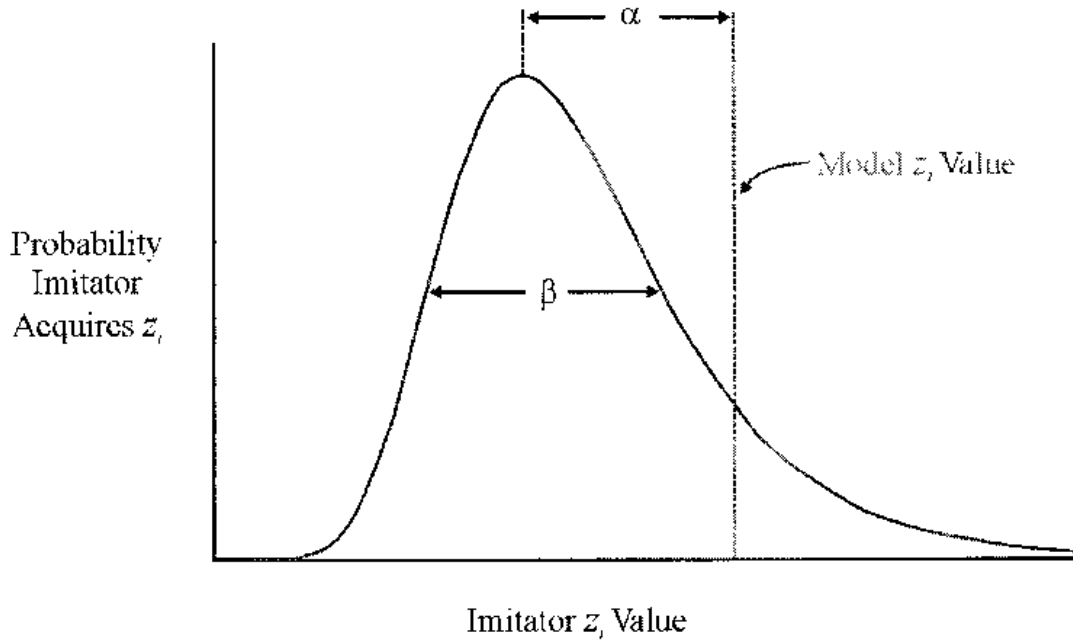


Figure 2. Gumbel distribution of imperfect transmission, reproduced from Henrich (2004). Analyses by Kobayashi and Aoki [46] confirm that this logic is not specific to Henrich’s chosen distribution.

The next factor we shall consider is the difference between the model skill and mean of learner skills, shown as  $\alpha$  in Figure 2. The  $\alpha$  parameter represents *transmission fidelity*. Higher transmission fidelity (lower  $\alpha$ ) increases mean cultural complexity. Finally, the  $\beta$  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  $\beta$ ) 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 and Carlino, Chatterjee and Hunt [104] show that urban density (a proxy for interconnectivity) predicts the rate of innovation. Similarly, Bettencourt et al. [105] 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 48].

In the laboratory, three independent sets of experiments [48-50] tested the relationship between sociality and cultural complexity<sup>2</sup>. 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. [48] also tested the effect of loss of sociality by starting with a generation of experts. Confirming theoretical predictions, with access to fewer models, skill was lost 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 [102]. Analyses of innovation within surgical techniques, as measured by patents and publications over the last 30 years, shows an

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<sup>2</sup> Consistent with other innovations, these key experimental results emerged close in time [48, 49 were published online on the same day]!

exponential increase in innovations [103]. 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 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. Models that make themselves more accessible or are better teachers [43, 44, 106].
2. Access to more models demonstrating variations in practices and skills [48].
3. An extended juvenile period, giving learners with more plastic brains more time to learn, better learning abilities (e.g. Theory of Mind), or 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). We discuss these in the next section. [For further examples, see 12, 107]
4. Finally, the content itself can simplify over time, with easier to remember steps or manufacturing techniques, thereby increasing transmission fidelity [108, 109]. 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. Although the changes required for the genesis of language are genetic (and may have evolved through gene-culture coevolution), language itself is subject to cultural evolution.

In Henrich's [110] 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 have 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) [111]. 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 [85]. In contrast, more tightness is associated with more incremental rather than radical innovation [84]. A related cross-culture difference is independence (or individualism) and interdependence (or collectivism), which may evolve for reasons that have little to do with innovation—recently, Talhelm et al. [112] have argued that within China, rice farming led to more interdependence compared to other kinds of farming. Like looseness, independence predicts higher innovation rates [113]. Acemoglu, Akcigit, and Celik [114] 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.

Overconfidence, which varies across societies, may be another important factor since it predicts more radical departures from current practices. Overconfident people are more likely to start a business [115] and take on more ambitious projects [116]. Although most entrepreneurs fail, theoretically, if the benefits far outweigh the costs, overconfidence can benefit individuals [117]. A few successes will

outweigh the many failures. However, even when this is not the case, overconfidence at a population level can benefit the group [118, 119], leading to more innovative societies. Societies can also affect transmission variance through policy and legislation.

The cost to benefit ratio of transmission variance is affected by economic conditions (e.g. market size) and legislation (e.g. patent laws) that reward innovations or reduce the costs of failure (e.g. bankruptcy laws, social safety nets). It is difficult to disentangle the effect of overall market size on the rate of innovation, since larger markets will tend to have higher sociality, which also increases innovation [in fact, markets may increase sociality 120]. Acemoglu and Linn [121] analyze the effect of *potential* market size (based on US demographics) for different categories of drugs; e.g., 0-20 year old use more antibiotics, whereas those 30 and older, use more antivirals. Their analyses reveal that the number of new drugs in each category is responsive to demographic trends, suggesting that innovations respond to incentives. Patent laws are another way to increase incentives for innovation by protecting innovators. However, as we have argued, recombination and incremental improvements are critical to innovation and patents can also stifle these processes. Historical analyses of patent laws by Moser [122] and recent analyses of human gene patents by Williams [123] both suggest that patent laws may often be too strong, reducing innovation, but this does not mean no patents would lead to more innovation. Qian [124] analyzed pharmaceutical patents in 92 countries from 1978 to 2002 using a matched sample technique. Her analyses suggest that there may be an optimal level of protection, after which innovation is stifled. Thus the collective brain perspective and empirical analyses both suggest that successful patent law is a delicate balance between rewarding innovations without stifling new innovations which incrementally build or recombine other innovations.

On the other end, reducing the costs of failure by creating a safety net can influence innovation via multiple channels, including by allowing to individuals to invest in broader social ties (expanding the

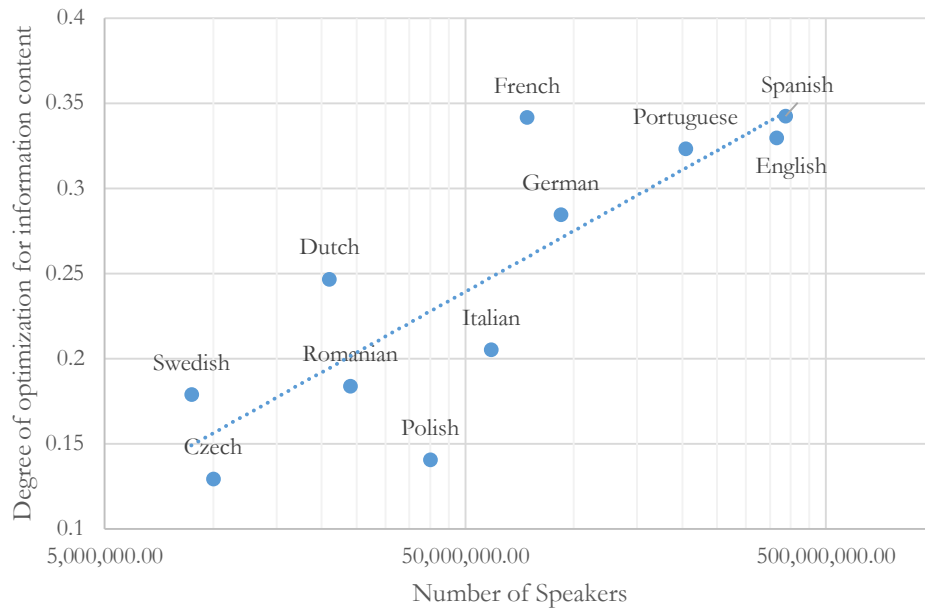
collective brain) over kin ties and by increasing entrepreneurship directly. This relationship is supported by analyses of England's Old Poor Law [125], more forgiving bankruptcy laws across 15 countries [126], unemployment insurance in France [127], and in the United States, the introduction of food stamps [128], health insurance for children [129] and access to health insurance unbundled from employment [130]. Of course, there's an optimal amount of social insurance vis-à-vis innovation, since increased funding such program can increase tax burdens—some data suggests that higher corporate taxes can lead to lower entrepreneurship [131, 132].

Although we have discussed sociality, transmission fidelity, and transmission variance separately, they are related and small changes affect all three. For example, sociality may have little effect if a task is too simple and therefore, transmission fidelity is very high [49]. Moreover, 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 language and pedagogy.

Just as myelination can make neural pathways more efficient over ontogeny, cultural evolution may optimize languages making collective brains more efficient. That is, if cultural evolution can hone languages in the same way it can shape toolkits and technologies, then we should predict that languages with larger speech communities should have greater communicative efficiency. In the laboratory, for example, transmission experiments with artificial languages reveal that over generations, these languages structurally change to become more learnable [133]. As with the technology experiments previously discussed, these underlying processes also scale-up to reveal population-level patterns.

To test the idea that cultural evolution has shaped communicative efficiency, we need some way to measure this efficiency. One method is to correlate the information content of words with their length. Less frequently used words generally contain more information, where information is a measure of predictability [134]. For example, in the sentence “It is raining so I should carry my \_\_\_\_\_”, “umbrella”

has far less information than “shotgun” since you could predict “umbrella” on the basis of the other words. Piantadosi et al. [135] used Google’s dataset of the 25,000 most frequently used strings in 11 European languages to measure the average information content of all words. They then correlated information content with word length. If languages are optimized for communicative efficiency, we should expect words with less information to be shorter. And if cultural evolution is shaping language as it does other cultural elements, we should predict a stronger correlation between word length and information for languages with more speakers. As Figure 3 illustrates, this is exactly what we find. The correlation between number of speakers [136] and the degree of optimization for a 4-word context [135] is astonishing:  $r = 0.83$ ,  $p = 0.002$ , with a 95% confidence interval (bootstrapped) ranging from  $r = 0.42$  to  $r = 0.89$ . Of course, these languages are phylogenetically related, and not statistically independent. Controlling for linguistic relatedness [using the tree provided by 137], we find the correlation between contrasts is  $r = 0.66$ ,  $p = 0.026$ , with a 95% confidence interval (bootstrapped) ranging from  $r = 0.26$  to  $r = 0.83$ .



**Figure 3. Relationship between the number of 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.**

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 [138] 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 [44, 139], thereby increasing transmission fidelity as cultural complexity increases. There is also some evidence for increases in division of labor (increased specialization), with more international trade and more domestic outsourcing of tasks (i.e. less vertical integration of all aspects of a business) [140, 141]. And despite these increases in pedagogy and specialization, our “extended juvenile period” has become further extended with delayed age of first child [142] and longer formal education [143]. American adults, for example, 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 varies 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 mechanism 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 more innovations should occur in larger, more interconnected collective brains [33, 104, 105] and among individuals with access to more and diverse information [99]. 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 accumulate abilities. Intelligence is often assumed to underlie innovation, and in principle it may increase transmission

fidelity. However, 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 [144]. 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 [99], as do individuals with higher openness to new experience (but not the other Big 5 personality traits) [145]. 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. Since a common assumption is that IQ leads to innovative ideas<sup>3</sup>, we will use IQ to illustrate the ways in which the collective brain can smarten cultural brains.

In a recent review of the intelligence literature, Nisbett et al. [147] suggest that there are still many unknowns and much controversy surrounding IQ data, let alone its interpretation. Based on their review, but avoiding interpretations and explanations, we have compiled a list of what seems probable given the current state of research. Note that, by “IQ”, we mean what 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 148].

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<sup>3</sup> Physicist Steven Hawkin famously replied to an interview question “What is your IQ?” with “I have no idea. People who boast about their IQ are losers” [146].

3. IQ may be separable into crystallized and fluid intelligence. Crystallized 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 SES.
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 Raven's test, a test that has been argued to be "culture-free" and a good measure of fluid intelligence.
7. IQ is lower among those who marry among closer kin or co-ethnics. More recently, genomic data suggests that higher heterosis predicts higher general cognitive ability [149].
8. IQ differences have neural correlates.
9. Sexes differ in IQ performance, including on subscales.
10. 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* [150]. Our smarts are substantially culturally acquired in ways that alter both our brains and biology, and cannot be measured independent of culture.

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. The difference between crystallized and

fluid intelligence is the difference between explicit knowledge and implicit styles of thinking, both of which vary across societies [151]. We will expand on this in the next section. For this reason, crystallized measures are more predictive of school performance than are fluid measures [152] 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 [153] 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 [154] 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 ( $R^2 = .008$ ). 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 155]. 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 population's stock of know-how, techniques, tools, tricks, etc. 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 an innate generalized abstract problem solving ability. The Flynn effect [for recent meta-analyses, see 156, 157] describes the steady increase in mean IQ since IQ tests were developed. If taken at face value, the Flynn effect renders previous generations barely functional, but by this account, the Flynn effect becomes a measure of increased mean cultural complexity. Understanding the collective brain give 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).

By this account, the “anti-Flynn effect” we see among populations who marry closer kin or co-ethnics may have less to do with genetic inbreeding and more to do with the loss of knowledge and skills we see when broad, non-kin-based sociality drops [48, 110]. By corollary, the increase we see with interethnic marriage may have less to do with heterosis (“hybrid vigor”) and more to do with exposure to more distinct, previously isolated ideas—cultural recombination. That any of these IQ differences have neural correlates is no more surprising than the neural changes caused by other experiences (it would be rather disturbing if they did not have neural correlates). See Henrich [12] for examples of

these changes and a discussion of how culture creates biological differences without creating genetic differences.

These arguments are relevant to sex differences and group differences. Sexes differ on IQ subscales just as they differ in the division of cultural know-how. Similarly, populations differ in IQ, also a cause of much controversy, and these differences correlate with various measures of economic and social development [158]. Although some [e.g. 158] 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. Some of these innovations may constrain or open new thought spaces, further raising IQ.

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. Moreover, all of this is not to say that there are no genetic differences between individuals that affect cognitive ability. 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. And while one could measure raw processing abilities, such as working memory and speed of thinking, by these measures chimpanzees are far smarter than we are [e.g. 159] and there is evidence that these “raw” abilities can also be trained [160]. 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. In the next section, we discuss one of the most neglected aspects of cultural evolution—how culture affects culture, opening new thought spaces.

## 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 that institutions, such as monogamous marriage, can affect crime rates, fertility, and gender inequality [161]. Agricultural practices can affect attitudes toward gender roles and female participation in the workforce, with effects persisting generations after families have given up farming [77]. 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. For example, 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. [162] 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. [163] 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. We can look to educational psychology to see how learning some skills improves others. For example, exposure to Socratic questioning improves critical thinking more generally [164], learning the method of loci (attaching items to a physical location in memory) improves performance on memory tests [165], and exposure to the history of Darwin's thought processes lead to a greater understanding of evolution [166]. These examples 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. For example, cross-cultural differences in analytic vs holistic thinking [167] have been argued to have implications for various other values, beliefs, and behaviors from the evaluation of brands [168] to the construction of built environments [169].

Ideas have interacted, recombined, and shaped each other throughout history and in doing so, they have opened up new thought spaces and constrained others. Henrich [12] offers many examples. 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! 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.

Systematic studies of historical texts may reveal the ways in which culture has shaped culture and opened thought spaces. Humans have a tendency to use the latest technology as an analogy for what we consider the greatest technology created by nature—ourselves. The 17<sup>th</sup> century was the era of sophisticated mechanical devices. In 1600 Galileo published *Le Meccaniche* (“On Mechanics”) and by 1642 Blaise Pascal had created the first mechanical calculator. It should come as no surprise that it was between 1641 and 1649 that Descartes wrote several works arguing that the human body is like a machine (controlled by a non-material mind or soul), including *Meditationes de Prima Philosophia* (“Meditations on First Philosophy”) in 1641 and *La description du corps humain* (“The Description of the Human Body”) in 1647. “And as a clock composed of wheels and counter-weights no less exactly observes the laws of nature when it is badly made, and does not show the time properly, than when it entirely satisfies the wishes of its maker, and as, if I consider the body of a man as being a sort of machine so built up and composed of nerves, muscles, veins, blood and skin...” [170]. Descartes wasn’t alone. Hobbes [171] goes further “For what is the ‘heart’ but a ‘spring’; and the ‘nerves’ but so many ‘strings’; and the ‘joints’ but so many ‘wheels,’ giving motion to the whole body, such as was

intended by the artificer?”. A century later, James Watts improved on the steam engine<sup>4</sup>, a key innovation helping to launch the Industrial Revolution. By the 19<sup>th</sup> century, the human body was likened to a steam engine; we see vestiges of this analogy in early 19<sup>th</sup> century idioms like “blowing off some steam” [172]. By the mid 20<sup>th</sup> century, the computing revolution had begun and today we have a new metaphor for the mind—a computational device—complete with permanent and temporary storage, input and output. For further discussion, see Muthukrishna [25].

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 have offered some ways 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 Ngrams; 173] and databases of history [e.g. 174] allows for systematic historical analyses of how the emergence of some ideas and technologies have allowed for the innovation of other ideas and technologies. 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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<sup>4</sup> As with other innovations in the collective brain, the steam engine is attributed to one man—James Watts—despite a long, traceable history. Basalla [93] traces this history, which can be summed up by his quoting of historian Joseph Needham: “No single man was the father of the steam engine; no single civilization either”.

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