
INNOVATION IN THE COLLECTIVE BRAIN

Michael Muthukrishna^{1,2}
Joseph Henrich¹

¹Department of Human Evolutionary Biology
Harvard University

²Department of Social Psychology
London School of Economics

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 rates of innovation are heavily influenced by (1) sociality, (2) transmission fidelity and (3) variance. We discuss some of the forces that affect these factors. These factors can also shape each other. For example, we show 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]. 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 *iklwa* short spear [9]. These savvy ancestors, who sometimes ascend to divine status, are often invoked to sanction 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) invented the lightbulb, Gutenberg the printing press, and Ford the automobile; that Newton invented “the 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 (e.g., Burke and Wills in Australia, Narváez and 300 conquistadors in the Americas [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 are linked into collective brains that 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, but they also affect each other. For example, cultural evolution may shape the transmission efficiency of languages. We perform a preliminary analysis on the efficiency of different languages, which suggest that languages with a larger number of speakers (higher sociality) are more efficient. 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, 18] and direct experimental evidence [19] suggest that larger brains are associated with greater cognitive ability, brain tissue is energetically expensive [19]. 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 [20, 21]. Another is to increase energy input by ensuring a reliable source of more calories [21]. 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, 22, 23]. 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. 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 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. Indeed, under some conditions, the model predicts an initial shrinking of brain size during the transition to heavy reliance on social learning, before increasing again in the realm of

cumulative culture. 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.

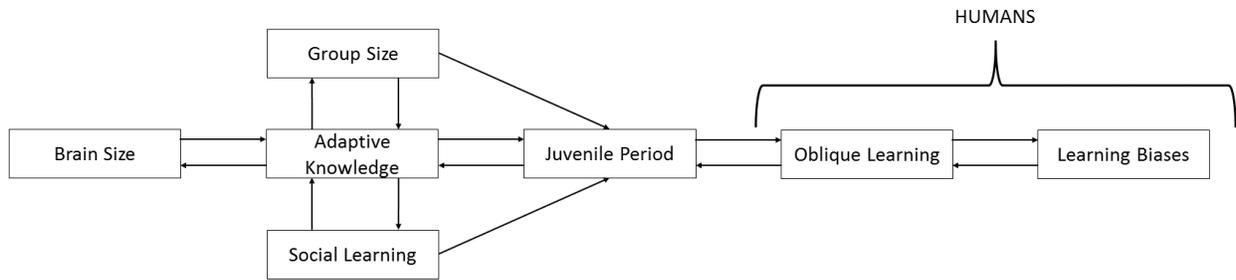


Figure 1. Causal relationships suggested by Cultural Brain Hypothesis.

The Cultural Brain Hypothesis predicts 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 weak to non-existent relationship between brain size 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 stronger relationship between brain size and group size (and other measures of sociality), since group size 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, many of which have been tested in the empirical literature.

The predictions made by the Cultural Brain Hypothesis 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 [18, 24, 25]. 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 [26]. This relationship is a byproduct of brains evolving to acquire adaptive knowledge, and is 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 [25, 27]. 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 [28]. 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 [29]. A byproduct of larger groups possessing more adaptive knowledge, which resulted in an extended juvenile period.
- (6) Group size and number of cultural traits [30, 31]. Larger groups of social learners possess more adaptive knowledge. This relationship is expected to be strongest in the realm of cumulative cultural evolution [32-36]—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. 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—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., 37, 38], 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 [39] estimate human transmission fidelity at 86%. This estimate simply suggests that human transmission fidelity is high. 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; 40]; proclivities, such as overimitation [41, 42]; social factors such as tolerance and pro-sociality [43, 44]; and culturally evolved innovations, such as teaching [45, 46]. Nevertheless, Claidière’s and Sperber’s [39] analyses also reveals that in domains such as food preferences, other animals like Norway rats, are capable of transmission of up to 95% fidelity. Norway rats don’t possess cumulative cultural evolution, thus transmission fidelity is a 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, the Cumulative Cultural Brain Hypothesis predicts that social learners in these co-evolutionary trajectories benefit from standing on the shoulders of smart asocial or individual learners. 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. This proposal is consistent with Reader et al.'s [47] analysis of 62 primate species, which suggests effective asocial learning in our evolutionary cousins. Note that the CBH assumes a trade-off between *time* invested learning by yourself vs learning from others; however, in our formalization, when selection for social learning drives bigger brains, asocial learning also improves, since asocial learning is dependent on brain size (whereas social learning is dependent on the abundance of knowledge). Thus, these social learners are capable of more potent asocial learning than their smaller brained ancestors, but engage in it less often. Hence, this theoretical feature of our model is consistent with Reader et al. [47], who find a positive correlation between asocial and social learning ability. We discuss the human extreme of this situation—social learning vastly improving asocial learning abilities—when we discuss how the collective brain fuels the cultural brain.

- (3) **Sociality.** Our model corroborates the results of previous models that suggest a causal relationship between sociality and cultural complexity [36, 48, 49]. This relationship is now supported by several independent experiments [32-34] and convergent field evidence [36, 48, 50-55]. 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 [56-61] with some evidence of cooperative breeding among modern hunter-gatherers [62]. Relatedly, other researchers have

emphasized the importance of pair-bonding [12, 63]. 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 [31, 64]. 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 a 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 home 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; 65, 66-68], direct and indirect cues that a potential model has adaptive know-how worth learning [e.g., success and prestige biases; 32, 69, 70], filtering mechanisms to assess the accuracy of information and sincerity of models [e.g., Credibility Enhancing Displays (CREDS); 71], personal relevance of culture [72, 73], and biases toward certain content (e.g., dangerous animals [74], the edibility of plants [75], fire [76], and gossip [77]). For further discussion, see Chudek et.al. [22] and Hoppitt and Laland [78], and for a further list of such strategies and biases, see Rendell et al. [68]. 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 [44]. 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 [79]. In the presence of inter-group competition, our ethnic psychology can lead to ingroup favoritism [80]. 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 [81]. 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, 82]. 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 genetic parents, and possibly a range of alloparents (aunts, uncles, grandmas, grandpas, 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. 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 83, 84]. Social norms governing family and kinship structure can affect the degree to which these smaller groups integrate into larger groups. For example, more outgroup marriage (exogamy) can bind former outgroups into larger cultural ingroups. Cutting across these groups are other connections and groupings that influence and structure cultural evolution. Sex is a good example and may represent one of the earliest “divisions of information”. For example, Fijian women have norms and taboos that help avoid teratogens during pregnancy, which Fijian men know very little about [85]. Alesina, Giuliano, and Nunn [86] show that societies that traditionally relied on plough-based agriculture have more sex-based division of labour than hoe-based societies, who have more equal gender norms (ploughing requires greater physical strength). These differences can persist even among descendants of these societies, born in other countries. Other cultural groupings include friendships and cliques [for a review, see 87], internally and externally recognized ethnicities [79, 80] and religious groups [88], formal institutions, castes, guilds and occupational specialization [89]. 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. Two key questions are: (1) how characteristic human network properties emerge from our ecology and psychology, and (2) the implications these properties. Here’s one example: analyzing the social networks across 24 species, Pasquaretta, et al. [90] show that more tolerant species, such as our own, have 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 across diverse human societies.

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 [91] with potential implications for the inflow of ideas from outgroups. Societies also differ in “tightness” and “looseness” [92]—their openness to divergent ideas—with consequent effects for cultural variance [93]. 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]! For example, though overconfidence will cause more individuals to fail after embarking on risky projects like starting a new business and striving to create a novel invention, it can also create societal-level benefits as those few who succeed generate the innovations that drive economic growth [94-96]. 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 [97] "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.

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) [36, 48, 49]. 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 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 98]. 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 hard rubber 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, 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 by prior cultural exposure to correctly recognise the accident as a discovery. How many others may have dropped rubber into fire, but failed to see the charred remains as a useful new product? Goodyear's discovery was serendipitous, but his prior exposure at the Roxbury India Rubber Company had made him aware of the need for vulcanization [99]. 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. 38, 100]. 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 [32], in the absence of systematic analyses of a random set of innovations, we are forced again to rely on case studies. The instances we discuss represent a few instances of hundreds [101]. 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, as nexus of ideas. In the case of Darwin and Wallace (co-discoverers of the principle of natural selection), both had read Thomas Malthus' essays and Robert Chambers' *Vestiges of the Natural History of Creation*, and both had travelled extensively among diverse islands [102]. In other 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, and the “inventor” is really just the popularizer [which also speaks to our need to identify the responsible Great Man; 97]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 [103]. Similarly, though Gutenberg made

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.

some improvements to the printing press, his real contribution was in popularizing techniques and technologies available at the time [104]. Other world-changing inventions, including the steam engine [105], automobile [106], telephone [107], and airplane [108], were gradual improvements and recombination of previous advancements, complete with accidental discoveries and controversy over who came first. Again, we have relied on examples to convey the predictions of a collective brain hypothesis. We hope to inspire more systematic scholarship to test the role of these processes in generating innovations. There are many ways that this might be achieved.

Several lines of evidence support the 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 [109] and bicycles [110], 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 [111] show that 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 its traditional or designed uses) [111]. 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 [32].

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. [112] 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 [113] and appears to have been increasing in recent times [114, 115], 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 [48] 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., 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*.

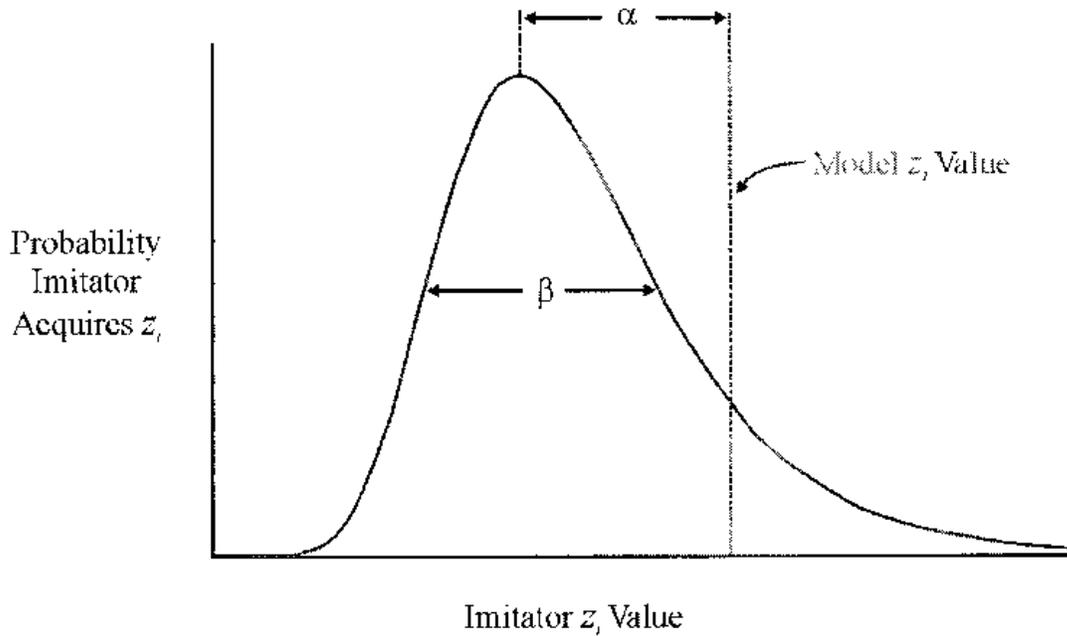


Figure 2. Gumbel distribution of imperfect transmission, reproduced from Henrich (2004). Analyses by Kobayashi and Aoki [49] confirm that this logic is not specific to Henrich’s chosen distribution.

The next factor we shall consider is the difference between the model skill and mean of learner skills, shown as 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 [30] show that both population size and island interconnectedness correlates with number of tools and tool complexity among Oceanic islands and Carlino, Chatterjee and Hunt [116] show that urban density (a proxy for interconnectivity) predicts the rate of innovation. Similarly, Bettencourt et al. [117] 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 32].

In the laboratory, three independent sets of experiments [32-34] tested the relationship between sociality and cultural complexity². 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. [32] 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

² Consistent with other innovations, these key experimental results emerged close in time [32, 33 were published online on the same day]—another case of simultaneous invention!

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 [114]. Analyses of innovation within surgical techniques, as measured by patents and publications over the last 30 years, shows an exponential increase in innovations [115]. 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. More social tolerance and prosociality—models that make themselves more accessible or are better teachers [45, 118, 119].
2. Access to more models demonstrating variations in practices and skills [32].
3. An extended juvenile period and/or longer lifespan, 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].
4. Finally, the content itself can simplify over time, with easier to remember steps or manufacturing techniques, thereby increasing transmission fidelity [120, 121]. 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 [122] 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) [123]. 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 [93]. In contrast, more tightness is associated with more incremental rather than radical innovation [92]. 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. Recently, Talhelm et al. [124] have argued that within China, rice farming led to more interdependence compared to other kinds of farming. Like looseness, independence predicts higher innovation rates [125]. Acemoglu, Akcigit, and Celik [126] 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 [96] and take on more ambitious projects [127]. Although most entrepreneurs fail, theoretically, if the benefits far outweigh the costs, overconfidence can benefit individuals [128]. 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 [94, 95], leading to more innovative societies more competitive in the intergroup competition of the world market [22, 129]. 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; 130]. Acemoglu and Linn [131] 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 (at least when firms are making decisions) 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 [132] and recent analyses of human gene patents by Williams [133] 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 [134] 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 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 [135], more forgiving bankruptcy laws across 15 countries [136], unemployment insurance in France [137], and in the United States, the introduction of food stamps [138], health insurance for children [139] and access to health insurance unbundled from employment [140], 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 [141, 142].

Although we have discussed sociality, transmission fidelity, and transmission variance separately, they are related and changes to one factor can affect the others. For example, sociality may have little effect if a task is too simple and therefore, transmission fidelity is very high [33]. Similarly, theoretical and experimental research with social network structures [143-146] 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're a long way from a completely connected network, human society will probably continue to

benefit from increases in interconnectivity (we're 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 [66]). Finally, the same principles that lead to larger populations possessing more complex technologies [e.g., 30] 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 [36, 48, 49, 147, 148]. 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 [149, 150], bigger phonemic inventories, more grammatical tools [12], and more learnable syntactic morphologies [151]. Paralleling the relationship between population and toolkit size [30, 48], Bromham, et al.'s [150] 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 [149]. In the laboratory, just as manufacturing steps become more efficient in technological transmission experiments [120], artificial language transmission experiments reveal that over generations, these languages structurally change to become more learnable [152]. Paralleling this in the real world, Lupyan and Dale [151] 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 doesn't 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 [153] test this hypothesis 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 [154]. 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 preceding words. Formally, Piantadosi et al. [153] 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 i th 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. [153] 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. We test if the word length-information correlation (the positive value of which we refer to as the degree of optimization) is stronger in languages with more speakers.

The correlation between the log of number of speakers³ (data from Ethnologue [155]) and the degree of optimization [153] 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 156] to calculate independent contrasts for the log of number of speakers and degree of optimization using the *pic* function in the R package *ape* [157]. 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 results are consistent with a collective brain hypothesis, though we emphasize that much more extensive investigation is necessary.

One potential alternative explanation for this relationship might be that optimization is somehow driven by number of adult second language speakers or some other feature of contact with other languages. However, unlike learnability [151], 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. [153], so we are unable to eliminate this as a possible explanation.

³ The analytic relationship in Henrich [48] 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 MM's website.

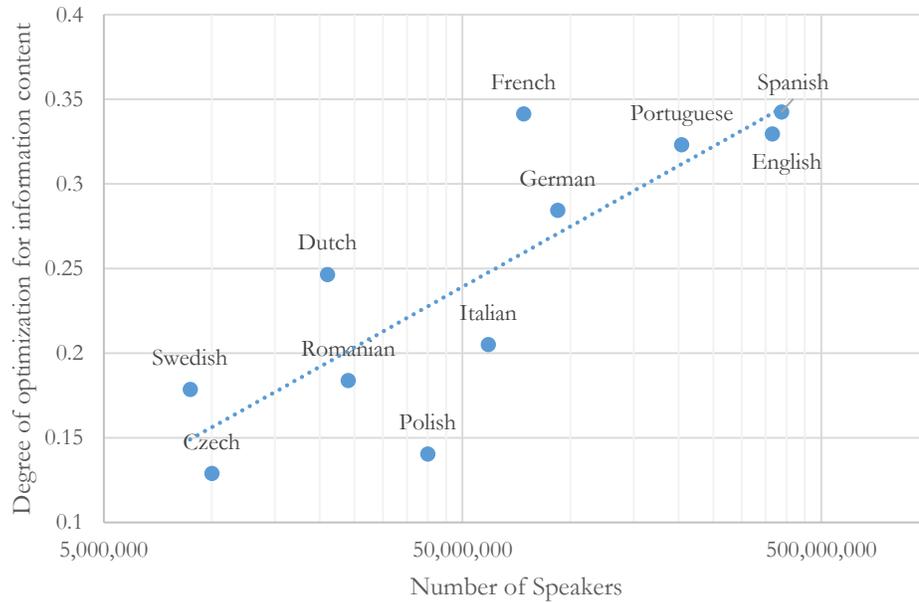


Figure 3. Relationship between the number of speakers of a language and the degree to which word lengths have been optimized for communication. The horizontal axis is a log scale. The vertical axis is the correlation between the information content of words and their written length made positive for 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 [158] 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 [119, 159], 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) [160, 161]. And despite these increases in pedagogy and specialization, our “extended juvenile period” has become further extended with delayed age of first child [162] and longer formal education [163]. Finally, American adults 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 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 more innovations should occur in larger, more interconnected collective brains [30, 116, 117] and among individuals with access to more and diverse information [111]. 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 creativity and innovation both between individuals [164] and

between populations [165-168]. 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 [164]. 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 [111], as do individuals with higher openness to new experience (but not the other Big 5 personality traits) [169]. 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 ideas⁴ by showing how the collective brain can increase the IQ of cultural brains.

In a recent review of the intelligence literature, Nisbett et al. [171] 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.

⁴ Physicist Stephen Hawking famously replied to an interview question “What is your IQ?” with “I have no idea. People who boast about their IQ are losers” [170].

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 172].
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 the corollary; higher heterosis predicts higher general cognitive ability [173].
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* [174]. Our smarts are substantially culturally acquired in ways that alter both our brains and biology, and cannot be measured 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 crystallized and fluid intelligence is the difference between explicit knowledge and implicit styles of thinking, both of which vary across societies [175]. We will expand on this in the next section. For this reason, crystallized measures are more predictive of school performance than are fluid measures [176] 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 [177] 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 [178] 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 179]. 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 180, 181] 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 development [182]. 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).

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 [32, 122]. And 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 [12]!).

These arguments are relevant to both sex 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 [165]. Although some [165-168] 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. 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, on these measures chimpanzees can beat us [e.g., 183] and these “raw” abilities may also be trained [184]. 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 reduce crime rates, fertility, and gender inequality [185]. Agricultural practices, such as hoe vs plough agriculture can affect attitudes toward gender roles and female participation in the workforce, with effects persisting generations after families have given up farming [86]. 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. [186] 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. [187] 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. Exposure to Socratic questioning improves critical thinking more generally [188], learning the method of loci (attaching items to a physical location in memory) improves performance on memory tests [189], and exposure to the history of Darwin's thought processes lead to a greater understanding of evolution [190]. 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 [191] have been argued to have implications for various other values, beliefs, and behaviors from the evaluation of brands [192] to the construction of built environments [193].

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 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 N-grams; 194] and databases of history [e.g., 195] 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.

REFERENCES

- [1] Laland, K.N., Odling-Smee, J. & Myles, S. 2010 How culture shaped the human genome: bringing genetics and the human sciences together. *Nature Reviews Genetics* **11**, 137-148.
- [2] Wilbert, J. 1993 *Mystic endowment: religious ethnography of the Warao Indians*. Cambridge, MA, Center for the Study of World Religions.
- [3] Mokyr, J. 1990 *The lever of riches: Technological creativity and economic progress*. Oxford, UK, Oxford University Press.
- [4] Mudrooroo. 1994 *Aboriginal Mythology: An AZ Spanning the History of the Australian Aboriginal People from the Earliest Legends to the Present Day*. London, UK, Thorsons.
- [5] Parpola, A. 2015 *The Roots of Hinduism: The Early Aryans and the Indus Civilization*, Oxford University Press, USA.
- [6] West, M.L. 1999 *Theogony and Works and days*. Oxford, UK, Oxford University Press.
- [7] Calverley, D.H. 1999 *Mysteries, Adventures and Indian Legends*. In *Calverley Collection* (Dawson Creek, BC, Dawson Creek Public Library).
- [8] Layton, R. 1992 *Australian rock art: a new synthesis*. Cambridge, UK, Cambridge University Press.
- [9] Morris, D.R. 1998 *The Washing of the Spears: A History of the Rise of the Zulu Nation under Shaka and its Fall in the Zulu War of 1879*. Boston, MA, Da Capo Press.
- [10] McNamara, R.A., Norenzayan, A. & Henrich, J. 2016 Supernatural punishment, in-group biases, and material insecurity: Experiments and Ethnography from Yasawa, Fiji. *Religion, Brain & Behavior* **6**, 34-55.
- [11] Pinker, S. 1997 *How the mind works*. New York, NY, W. W. Norton & Company.
- [12] Henrich, J. 2016 *The secret of our success: How culture is driving human evolution, domesticating our species, and making us smarter*. Princeton, NJ, Princeton University Press.
- [13] Bailey, D.H. & Geary, D.C. 2009 Hominid brain evolution. *Human Nature* **20**, 67-79.
- [14] Striedter, G.F. 2005 *Principles of brain evolution*. Sunderland, MA, Sinauer Associates.
- [15] Roth, G. & Dicke, U. 2005 Evolution of the brain and intelligence. *Trends in cognitive sciences* **9**, 250-257.
- [16] Shultz, S. & Dunbar, R. 2010 Encephalization is not a universal macroevolutionary phenomenon in mammals but is associated with sociality. *Proceedings of the National Academy of Sciences* **107**, 21582-21586.
- [17] Deaner, R.O., Isler, K., Burkart, J. & van Schaik, C. 2007 Overall brain size, and not encephalization quotient, best predicts cognitive ability across non-human primates. *Brain, Behavior and Evolution* **70**, 115-124.
- [18] MacLean, E.L., Hare, B., Nunn, C.L., Addessi, E., Amici, F., Anderson, R.C., Aureli, F., Baker, J.M., Bania, A.E., Barnard, A.M., et al. 2014 The evolution of self-control. *Proceedings of the National Academy of Sciences of the United States of America* **111**, E2140-E2148.
- [19] Kotschal, A., Rogell, B., Bundsen, A., Svensson, B., Zajitschek, S., Brännström, I., Immler, S., Maklakov, A.A. & Kolm, N. 2013 Artificial selection on relative brain size in the guppy reveals costs and benefits of evolving a larger brain. *Current Biology* **23**, 168-171.

- [20] Tsuboi, M., Husby, A., Kotrschal, A., Hayward, A., Buechel, S.D., Zidar, J., Løvlie, H. & Kolm, N. 2015 Comparative support for the expensive tissue hypothesis: Big brains are correlated with smaller gut and greater parental investment in Lake Tanganyika cichlids. *Evolution* **69**, 190-200.
- [21] Navarrete, A., van Schaik, C.P. & Isler, K. 2011 Energetics and the evolution of human brain size. *Nature* **480**, 91-93.
- [22] Chudek, M., Muthukrishna, M. & Henrich, J. 2015 Cultural Evolution. In *The Handbook of Evolutionary Psychology* (ed. D.M. Buss), 2nd ed. Hoboken, NJ, John Wiley and Sons.
- [23] Dean, L.G., Vale, G.L., Laland, K.N., Flynn, E. & Kendal, R.L. 2014 Human cumulative culture: a comparative perspective. *Biological Reviews* **89**, 284-301.
- [24] Sol, D., Bacher, S., Reader, S.M. & Lefebvre, L. 2008 Brain size predicts the success of mammal species introduced into novel environments. *The American Naturalist* **172**, S63-S71.
- [25] Reader, S.M. & Laland, K.N. 2002 Social intelligence, innovation, and enhanced brain size in primates. *Proceedings of the National Academy of Sciences* **99**, 4436-4441.
- [26] Dunbar, R.I. & Shultz, S. 2007 Evolution in the social brain. *Science* **317**, 1344-1347.
- [27] Lefebvre, L. 2013 Brains, innovations, tools and cultural transmission in birds, non-human primates, and fossil hominins. *Frontiers in human neuroscience* **7**.
- [28] Charvet, C.J. & Finlay, B.L. 2012 Embracing covariation in brain evolution: large brains, extended development, and flexible primate social systems. *Progress in brain research* **195**, 71.
- [29] Joffe, T.H. 1997 Social pressures have selected for an extended juvenile period in primates. *Journal of human evolution* **32**, 593-605.
- [30] Kline, M.A. & Boyd, R. 2010 Population size predicts technological complexity in Oceania. *Proceedings of the Royal Society B: Biological Sciences* **277**, 2559-2564.
- [31] Lind, J. & Lindenfors, P. 2010 The number of cultural traits is correlated with female group size but not with male group size in chimpanzee communities. *PloS one* **5**, e9241.
- [32] Muthukrishna, M., Shulman, B.W., Vasilescu, V. & Henrich, J. 2013 Sociality influences cultural complexity. *Proceedings of the Royal Society B: Biological Sciences* **281**, 20132511.
- [33] Derex, M., Beugin, M.-P., Godelle, B. & Raymond, M. 2013 Experimental evidence for the influence of group size on cultural complexity. *Nature* **503**, 389-391.
- [34] Kempe, M. & Mesoudi, A. 2014 An experimental demonstration of the effect of group size on cultural accumulation. *Evolution and Human Behavior* **35**, 285-290.
- [35] Henrich, J. 2004 Cultural group selection, coevolutionary processes and large-scale cooperation. *Journal of Economic Behavior & Organization* **53**, 3-35.
- [36] Powell, A., Shennan, S. & Thomas, M.G. 2009 Late Pleistocene demography and the appearance of modern human behavior. *Science* **324**, 1298-1301.
- [37] Enquist, M., Strimling, P., Eriksson, K., Laland, K. & Sjostrand, J. 2010 One cultural parent makes no culture. *Animal Behaviour* **79**, 1353-1362.
- [38] Lewis, H.M. & Laland, K.N. 2012 Transmission fidelity is the key to the build-up of cumulative culture. *Philosophical Transactions of the Royal Society B: Biological Sciences* **367**, 2171-2180.
- [39] Claidière, N. & Sperber, D. 2010 Imitation explains the propagation, not the stability of animal culture. *Proceedings of the Royal Society B: Biological Sciences* **277**, 651-659.
- [40] Herrmann, E., Call, J., Hernández-Lloreda, M.V., Hare, B. & Tomasello, M. 2007 Humans have evolved specialized skills of social cognition: the cultural intelligence hypothesis. *Science* **317**, 1360-1366.
- [41] Whiten, A., McGuigan, N., Marshall-Pescini, S. & Hopper, L.M. 2009 Emulation, imitation, over-imitation and the scope of culture for child and chimpanzee. *Philosophical Transactions of the Royal Society B: Biological Sciences* **364**, 2417-2428.
- [42] Nielsen, M., Subiaul, F., Galef, B., Zentall, T. & Whiten, A. 2012 Social learning in humans and nonhuman animals: theoretical and empirical dissections. *Journal of Comparative Psychology* **126**, 109.

- [43] Bell, A.V., Richerson, P.J. & McElreath, R. 2009 Culture rather than genes provides greater scope for the evolution of large-scale human prosociality. *Proceedings of the National Academy of Sciences* **106**, 17671-17674.
- [44] Chudek, M. & Henrich, J. 2011 Culture–gene coevolution, norm-psychology and the emergence of human prosociality. *Trends in cognitive sciences* **15**, 218-226.
- [45] Morgan, T.J.H., Uomini, N.T., Rendell, L.E., Chouinard-Thuly, L., Street, S.E., Lewis, H.M., Cross, C.P., Evans, C., Kearney, R., de la Torre, I., et al. 2015 Experimental evidence for the co-evolution of hominin tool-making teaching and language. *Nature Communications* **6**.
- [46] Kline, M.A. 2014 How to learn about teaching: An evolutionary framework for the study of teaching behavior in humans and other animals. *Behavioral and Brain Sciences* **FirstView**, 1-70. (doi:doi:10.1017/S0140525X14000090).
- [47] Reader, S.M., Hager, Y. & Laland, K.N. 2011 The evolution of primate general and cultural intelligence. *Philosophical Transactions of the Royal Society B: Biological Sciences* **366**, 1017-1027.
- [48] Henrich, J. 2004 Demography and cultural evolution: how adaptive cultural processes can produce maladaptive losses: the Tasmanian case. *American Antiquity* **69**, 197-214.
- [49] Kobayashi, Y. & Aoki, K. 2012 Innovativeness, population size and cumulative cultural evolution. *Theoretical Population Biology* **82**, 38-47.
- [50] Kline, M.A. & Boyd, R. 2010 Population size predicts technological complexity in Oceania. *P R Soc B* **277**, 2559-2564.
- [51] Edinborough, K. 2009 Population history, abrupt climate change, and evolution of arrowhead technology in Mesolithic south Scandinavia. (pp. 191-202, Berkeley, CA: University of California Press.
- [52] Marquet, P.A., Santoro, C.M., Latorre, C., Standen, V.G., Abades, S.R., Rivadeneira, M.M., Arriaza, B. & Hochberg, M.E. 2012 Emergence of social complexity among coastal hunter-gatherers in the Atacama Desert of northern Chile. *Proceedings of the National Academy of Sciences* **109**, 14754-14760.
- [53] Wadley, L., Sievers, C., Bamford, M., Goldberg, P., Berna, F. & Miller, C. 2011 Middle Stone Age bedding construction and settlement patterns at Sibudu, South Africa. *Science* **334**, 1388-1391.
- [54] Collard, M., Ruttle, A., Buchanan, B. & O'Brien, M.J. 2012 Risk of Resource Failure and Toolkit Variation in Small-Scale Farmers and Herders. *Plos One* **7**, e40975.
- [55] van Schaik, C.P., Ancrenaz, M., Gwendolyn, B., Galdikas, B., Knott, C.D., Singeton, I., Suzuki, A., Utami, S.S. & Merrill, M. 2003 Orangutan Cultures and the Evolution of Material Culture. *Science* **299**, 102-105.
- [56] Mace, R. & Sear, R. 2005 Are humans cooperative breeders? In *Grandmotherhood: the evolutionary significance of the second half of female life* (eds. E. Voland, A. Chasiotis & W. Schiefenhövel), pp. 143–159. New Brunswick, NJ, Rutgers University Press.
- [57] Burkart, J.M., Hrdy, S.B. & Van Schaik, C.P. 2009 Cooperative breeding and human cognitive evolution. *Evolutionary Anthropology* **18**, 175-186.
- [58] Kaplan, H. & Gurven, M. 2005 The natural history of human food sharing and cooperation: a review and a new multi-individual approach to the negotiation of norms. In *Moral sentiments and material interests: The foundations of cooperation in economic life* (eds. H. Gintis, S. Bowles, R. Boyd & E. Fehr), pp. 75-113. Cambridge, MA, MIT Press.
- [59] Wiessner, P. 2002 Hunting, healing, and hxaro exchange: A long-term perspective on! Kung (Ju/'hoansi) large-game hunting. *Evolution and Human Behavior* **23**, 407-436.
- [60] Hrdy, S.B. 2009 *Mothers and others: the evolutionary origins of mutual understanding*. Cambridge, MA, Harvard University Press.
- [61] Emlen, S.T. 1995 An evolutionary theory of the family. *Proceedings of the National Academy of Sciences* **92**, 8092-8099.

- [62] Hill, K. & Hurtado, A.M. 2009 Cooperative breeding in South American hunter–gatherers. *Proceedings of the Royal Society B: Biological Sciences* **276**, 3863-3870.
- [63] Chapais, B. 2009 *Primeval kinship: How pair-bonding gave birth to human society*. Cambridge, MA, Harvard University Press.
- [64] Boesch, C. 1991 Teaching among wild chimpanzees. *Animal Behaviour* **41**, 530-532.
- [65] Boyd, R. & Richerson, P.J. 1985 *Culture and the evolutionary process*. Chicago, IL, University of Chicago Press.
- [66] Muthukrishna, M., Morgan, T.J.H. & Henrich, J. forthcoming The When and Who of Social Learning and Conformist Transmission. *Evolution and Human Behavior*.
- [67] Morgan, T.J.H., Laland, K.N. & Harris, P.L. 2014 The development of adaptive conformity in young children: effects of uncertainty and consensus. *Developmental Science*.
- [68] Rendell, L., Fogarty, L., Hoppitt, W.J., Morgan, T.J., Webster, M.M. & Laland, K.N. 2011 Cognitive culture: theoretical and empirical insights into social learning strategies. *Trends in cognitive sciences* **15**, 68-76.
- [69] Henrich, J. & Gil-White, F.J. 2001 The evolution of prestige: Freely conferred deference as a mechanism for enhancing the benefits of cultural transmission. *Evolution and human behavior* **22**, 165-196.
- [70] Chudek, M., Heller, S., Birch, S.A. & Henrich, J. 2012 Prestige-biased cultural learning: bystander's differential attention to potential models influences children's learning. *Evolution and Human Behavior* **33**, 46-56.
- [71] Henrich, J. 2009 The evolution of costly displays, cooperation and religion: Credibility enhancing displays and their implications for cultural evolution. *Evolution and Human Behavior* **30**, 244-260.
- [72] Hilmert, C.J., Kulik, J.A. & Christenfeld, N.J. 2006 Positive and negative opinion modeling: The influence of another's similarity and dissimilarity. *Journal of personality and social psychology* **90**, 440-452.
- [73] Kinzler, K.D., Corriveau, K.H. & Harris, P.L. 2011 Children's selective trust in native-accented speakers. *Developmental science* **14**, 106-111.
- [74] Barrett, H.C. & Broesch, J. 2012 Prepared social learning about dangerous animals in children. *Evolution and Human Behavior* **33**, 499-508.
- [75] Wertz, A.E. & Wynn, K. 2014 Selective social learning of plant edibility in 6-and 18-month-old infants. *Psychological science* **25**, 874-882.
- [76] Fessler, D.M. 2006 A burning desire: steps toward an evolutionary psychology of fire learning. **6**, 429-451.
- [77] Mesoudi, A., Whiten, A. & Dunbar, R. 2006 A bias for social information in human cultural transmission. *British Journal of Psychology* **97**, 405-423.
- [78] Hoppitt, W. & Laland, K.N. 2013 *Social Learning: An Introduction to Mechanisms, Methods, and Models*. Princeton, NJ, Princeton University Press.
- [79] McElreath, R., Boyd, R. & Richerson, P.J. 2003 Shared norms and the evolution of ethnic markers. *Current Anthropology* **44**, 122-130.
- [80] Efferson, C., Lalive, R. & Fehr, E. 2008 The coevolution of cultural groups and ingroup favoritism. *Science* **321**, 1844-1849.
- [81] Tajfel, H., Billig, M.G., Bundy, R.P. & Flament, C. 1971 Social categorization and intergroup behaviour. *European journal of social psychology* **1**, 149-178.
- [82] Hill, K.R., Walker, R.S., Božičević, M., Eder, J., Headland, T., Hewlett, B., Hurtado, A.M., Marlowe, F., Wiessner, P. & Wood, B. 2011 Co-residence patterns in hunter-gatherer societies show unique human social structure. *Science* **331**, 1286-1289.
- [83] Johnson, A.W. & Earle, T.K. 2000 *The evolution of human societies: from foraging group to agrarian state*. Stanford, CA, Stanford University Press.

- [84] Flannery, K. 2012 *The creation of inequality: how our prehistoric ancestors set the stage for monarchy, slavery, and empire*. Cambridge, MA, Harvard University Press.
- [85] Henrich, J. & Henrich, N. 2010 The evolution of cultural adaptations: Fijian food taboos protect against dangerous marine toxins. *Proceedings of the Royal Society B: Biological Sciences* **277**, 3715-3724.
- [86] Alesina, A., Giuliano, P. & Nunn, N. 2013 On the Origins of Gender Roles: Women and the Plough. *The Quarterly Journal of Economics* **128**, 469-530.
- [87] Hruschka, D.J. 2010 *Friendship: Development, ecology, and evolution of a relationship*. Berkeley, CA, University of California Press.
- [88] Norenzayan, A. 2013 *Big gods: How religion transformed cooperation and conflict*. Princeton, NJ, Princeton University Press.
- [89] Henrich, J. & Boyd, R. 2008 Division of labor, economic specialization, and the evolution of social stratification. *Current Anthropology* **49**, 715-724.
- [90] Pasquaretta, C., Leve, M., Claidiere, N., van de Waal, E., Whiten, A., MacIntosh, A.J.J., Pele, M., Bergstrom, M.L., Borgeaud, C., Brosnan, S.F., et al. 2014 Social networks in primates: smart and tolerant species have more efficient networks. *Scientific reports* **4**.
- [91] Hruschka, D., Efferson, C., Jiang, T., Falletta-Cowden, A., Sigurdsson, S., McNamara, R., Sands, M., Munira, S., Slingerland, E. & Henrich, J. 2014 Impartial Institutions, Pathogen Stress and the Expanding Social Network. *Human Nature* **25**, 567-579.
- [92] Gelfand, M.J., Nishii, L.H. & Raver, J.L. 2006 On the nature and importance of cultural tightness-looseness. *Journal of Applied Psychology* **91**, 1225.
- [93] Uz, I. 2015 The Index of Cultural Tightness and Looseness Among 68 Countries. *Journal of Cross-Cultural Psychology* **46**, 319-335.
- [94] Acs, Z. 2006 How is entrepreneurship good for economic growth? *Innovations* **1**, 97-107.
- [95] Bernardo, A.E. & Welch, I. 2001 On the evolution of overconfidence and entrepreneurs. *Journal of Economics & Management Strategy* **10**, 301-330.
- [96] Camerer, C. & Lovallo, D. 1999 Overconfidence and excess entry: An experimental approach. *American economic review* **89**, 306-318.
- [97] Carlyle, T. 1841 *On heroes, hero-worship, and the heroic in history*. London, UK, James Fraser.
- [98] Roberts, R.M. 1989 *Serendipity: Accidental discoveries in science*. Hoboken, NJ, John Wiley & Sons.
- [99] Slack, C. 2002 *Noble obsession: Charles Goodyear, Thomas Hancock, and the race to unlock the greatest industrial secret of the nineteenth century*. New York, NY, Hyperion.
- [100] Enquist, M., Ghirlanda, S. & Eriksson, K. 2011 Modelling the evolution and diversity of cumulative culture. *Philosophical Transactions of the Royal Society B: Biological Sciences* **366**, 412-423.
- [101] Merton, R.K. 1963 Resistance to the systematic study of multiple discoveries in science. *European Journal of Sociology* **4**, 237-282.
- [102] Raby, P. 2001 *Alfred Russel Wallace: A Life*. Princeton, NJ, Princeton University Press.
- [103] Friedel, R. & Israel, P.B. 2010 *Edison's Electric Light: The Art of Invention*. Baltimore, MD, Johns Hopkins University Press.
- [104] Diamond, J. 1999 Invention is the mother of necessity. *The New York Times Magazine*, 142-144.
- [105] Basalla, G. 1988 *The evolution of technology*. Cambridge, UK, Cambridge University Press.
- [106] Eckermann, E. 2001 *World history of the automobile*. Warrenfale, PA, Society of Automotive Engineers.
- [107] Hounshell, D.A. 1975 Elisha Gray and the telephone: On the disadvantages of being an expert. *Technology and culture* **16**, 133-161.
- [108] Hallion, R. 2003 *Taking flight: inventing the aerial age, from antiquity through the First World War*. Oxford, UK, Oxford University Press.
- [109] Lyman, R.L. & O'Brien, M.J. 2000 Measuring and explaining change in artifact variation with clade-diversity diagrams. *Journal of Anthropological Archaeology* **19**, 39-74.

- [110] Lake, M.W. & Venti, J. 2009 Quantitative Analysis of Macroevolutionary Patterning in Technological Evolution. In *Pattern and process in cultural evolution* (ed. S. Shennan), p. 147. Los Angeles, CA, University of California Press.
- [111] Maddux, W.W., Adam, H. & Galinsky, A.D. 2010 When in Rome... Learn why the Romans do what they do: How multicultural learning experiences facilitate creativity. *Personality and Social Psychology Bulletin* **36**, 731-741.
- [112] Isaacson, W. 2007 *Einstein: His life and universe*. New York, NY, Simon and Schuster.
- [113] Diamond, J.M. 1997 *Guns, germs and steel*. New York, NY, W. W. Norton.
- [114] Comin, D. & Hobijn, B. 2010 An Exploration of Technology Diffusion. *American Economic Review* **100**, 2031-2059.
- [115] Hughes-Hallett, A., Mayer, E.K., Marcus, H.J., Cundy, T.P., Pratt, P.J., Parston, G., Vale, J.A. & Darzi, A.W. 2014 Quantifying innovation in surgery. *Annals of surgery* **260**, 205-211.
- [116] Carlino, G.A., Chatterjee, S. & Hunt, R.M. 2007 Urban density and the rate of invention. *Journal of Urban Economics* **61**, 389-419.
- [117] Bettencourt, L.M., Lobo, J., Helbing, D., Kühnert, C. & West, G.B. 2007 Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the national academy of sciences* **104**, 7301-7306.
- [118] Fogarty, L., Strimling, P. & Laland, K.N. 2011 The evolution of teaching. *Evolution* **65**, 2760-2770.
- [119] Kline, M.A. 2015 How to learn about teaching: An evolutionary framework for the study of teaching behavior in humans and other animals. *Behavioral and Brain Sciences* **38**, 1-70. (doi:doi:10.1017/S0140525X14000090).
- [120] Flynn, E. 2008 Investigating children as cultural magnets: do young children transmit redundant information along diffusion chains? *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 3541-3551.
- [121] Caldwell, C.A. & Smith, K. 2012 Cultural evolution and perpetuation of arbitrary communicative conventions in experimental microsocieties. *PLoS one* **7**, e43807.
- [122] Henrich, J. 2004 Demography and Cultural Evolution: Why adaptive cultural processes produced maladaptive losses in Tasmania. *American Antiquity* **69**, 197-214.
- [123] Gelfand, M.J., Raver, J.L., Nishii, L., Leslie, L.M., Lun, J., Lim, B.C., Duan, L., Almaliach, A., Ang, S. & Arnadottir, J. 2011 Differences between tight and loose cultures: A 33-nation study. *Science* **332**, 1100-1104.
- [124] Talhelm, T., Zhang, X., Oishi, S., Shimin, C., Duan, D., Lan, X. & Kitayama, S. 2014 Large-scale psychological differences within China explained by rice versus wheat agriculture. *Science* **344**, 603-608.
- [125] Gorodnichenko, Y. & Roland, G. 2011 Individualism, innovation, and long-run growth. *Proceedings of the National Academy of Sciences* **108**, 21316-21319.
- [126] Acemoglu, D., Akcigit, U. & Celik, M.A. 2014 Young, restless and creative: Openness to disruption and creative innovations. In *National Bureau of Economic Research* (
- [127] Bénabou, R. & Tirole, J. 2002 Self-confidence and personal motivation. *The Quarterly Journal of Economics* **117**, 871-915.
- [128] Johnson, D.D. & Fowler, J.H. 2011 The evolution of overconfidence. *Nature* **477**, 317-320.
- [129] Richerson, P., Baldini, R., Bell, A., Demps, K., Frost, K., Hillis, V., Mathew, S., Newton, E., Narr, N., Newson, L., et al. forthcoming Cultural Group Selection Plays an Essential Role in Explaining Human Cooperation: A Sketch of the Evidence. *Behavioral and Brain Sciences*.
- [130] Henrich, J., Ensminger, J., Barr, A. & McElreath, R. 2014 Empirical results—markets, community size, religion and the nature of human sociality. In *Experimenting with social norms: Fairness and punishment in cross-cultural perspective* (eds. J. Ensminger & J. Henrich), pp. 89-148. New York, NY, Russell Sage Foundation.

- [131] Acemoglu, D. & Linn, J. 2004 Market Size in Innovation: Theory and Evidence from the Pharmaceutical Industry. *The Quarterly Journal of Economics* **119**, 1049-1090.
- [132] Moser, P. 2013 Patents and Innovation: Evidence from Economic History. *The Journal of Economic Perspectives* **27**, 23-44.
- [133] Williams, H.L. 2010 Intellectual property rights and innovation: Evidence from the human genome. *The journal of political economy* **121**, 1-27.
- [134] Qian, Y. 2007 Do National Patent Laws Stimulate Domestic Innovation in a Global Patenting Environment? A Cross-Country Analysis of Pharmaceutical Patent Protection, 1978–2002. *Review of Economics and Statistics* **89**, 436-453.
- [135] Greif, A. & Iyigun, M. 2012 Social Institutions, Violence and Innovations: Did the Old Poor Law Matter? In *Working Paper* (
- [136] Armour, J. & Cumming, D. 2008 Bankruptcy law and entrepreneurship. *American Law and Economics Review* **10**, 303-350.
- [137] Hombert, J., Schoar, A., Sraer, D. & Thesmar, D. 2014 Can Unemployment Insurance Spur Entrepreneurial Activity? In *National Bureau of Economic Research* (
- [138] Olds, G. 2014 Food Stamp Entrepreneurs. (Working Paper.
- [139] Olds, G. 2014 Immigrant Entrepreneurs and the Social Safety Net. (Working Paper.
- [140] Fairlie, R.W., Kapur, K. & Gates, S. 2011 Is employer-based health insurance a barrier to entrepreneurship? *Journal of Health Economics* **30**, 146-162.
- [141] Djankov, S., Ganser, T., McLiesh, C., Ramalho, R. & Shleifer, A. 2008 The effect of corporate taxes on investment and entrepreneurship. In *National Bureau of Economic Research* (
- [142] Mukherjee, A., Singh, M. & Zaldokas, A. 2015 Do Corporate Taxes Hinder Innovation? In *Working Paper* (
- [143] Lazer, D. & Friedman, A. 2007 The network structure of exploration and exploitation. *Administrative Science Quarterly* **52**, 667-694.
- [144] Kollman, K., Miller, J.H. & Page, S.E. 2000 Decentralization and the search for policy solutions. *Journal of Law, Economics, and Organization* **16**, 102-128.
- [145] Derex, M. & Boyd, R. 2015 The foundations of the human cultural niche. *Nature Communications* **6**.
- [146] Mason, W.A., Jones, A. & Goldstone, R.L. 2008 Propagation of innovations in networked groups. *Journal of Experimental Psychology: General* **137**, 422.
- [147] Aoki, K. & Feldman, M.W. 2014 Evolution of learning strategies in temporally and spatially variable environments: a review of theory. *Theoretical population biology* **91**, 3-19.
- [148] Aoki, K., Lehmann, L. & Feldman, M.W. 2011 Rates of cultural change and patterns of cultural accumulation in stochastic models of social transmission. *Theoretical Population Biology* **79**, 192-202.
- [149] Deutscher, G. 2011 *Through the language glass: Why the world looks different in other languages*. New York, NY, Random House.
- [150] Bromham, L., Hua, X., Fitzpatrick, T.G. & Greenhill, S.J. 2015 Rate of language evolution is affected by population size. *Proceedings of the National Academy of Sciences* **112**, 2097-2102.
- [151] Lupyán, G. & Dale, R. 2010 Language Structure Is Partly Determined by Social Structure. *PLoS ONE* **5**, e8559.
- [152] Kirby, S., Cornish, H. & Smith, K. 2008 Cumulative cultural evolution in the laboratory: An experimental approach to the origins of structure in human language. *Proceedings of the National Academy of Sciences* **105**, 10681-10686.
- [153] Piantadosi, S.T., Tily, H. & Gibson, E. 2011 Word lengths are optimized for efficient communication. *Proceedings of the National Academy of Sciences* **108**, 3526-3529.
- [154] Shannon, C.E. 2001 A mathematical theory of communication. *ACM SIGMOBILE Mobile Computing and Communications Review* **5**, 3-55.

- [155] Lewis, M.P., Simons, G.F. & Fennig, C.D. 2015 *Ethnologue: Languages of the World*. (Dallas, TX, SIL International).
- [156] Bouckaert, R., Lemey, P., Dunn, M., Greenhill, S.J., Alekseyenko, A.V., Drummond, A.J., Gray, R.D., Suchard, M.A. & Atkinson, Q.D. 2012 Mapping the origins and expansion of the Indo-European language family. *Science* **337**, 957-960.
- [157] Paradis, E., Claude, J. & Strimmer, K. 2004 APE: analyses of phylogenetics and evolution in R language. *Bioinformatics* **20**, 289-290.
- [158] Mesoudi, A. 2011 Variable cultural acquisition costs constrain cumulative cultural evolution. *PloS one* **6**, e18239.
- [159] Kline, M.A., Boyd, R. & Henrich, J. forthcoming Teaching and the life history of cultural transmission in Fijian villages. *Human Nature*.
- [160] Meyer, T. & Schuler, F. 2012 Outsourcing: division of labour gives competitive edge. In *Outsourcing Europa* (ed. T.O. Journal), pp. 4-9.
- [161] Munch, J.R. & Skaksen, J.R. 2009 Specialization, outsourcing and wages. *Review of world economics* **145**, 57-73.
- [162] Mathews, T., Hamilton, B.E. & National Center for Health Statistics. 2009 Delayed childbearing: more women are having their first child later in life.
- [163] Patten, E. & Fry, R. 2015 How Millennials today compare with their grandparents 50 years ago. In *Fact Tank* (Washington, DC, Pew Research Centre).
- [164] Jauk, E., Benedek, M., Dunst, B. & Neubauer, A.C. 2013 The relationship between intelligence and creativity: New support for the threshold hypothesis by means of empirical breakpoint detection. *Intelligence* **41**, 212-221.
- [165] Lynn, R. & Vanhanen, T. 2006 *IQ and global inequality*. Augusta, GA, Washington Summit Publishers.
- [166] Rindermann, H. 2012 Intellectual classes, technological progress and economic development: The rise of cognitive capitalism. *Personality and Individual Differences* **53**, 108-113.
- [167] Rindermann, H. & Thompson, J. 2011 Cognitive Capitalism The Effect of Cognitive Ability on Wealth, as Mediated Through Scientific Achievement and Economic Freedom. *Psychological Science* **22**, 754-763.
- [168] Burhan, N.A.S., Mohamad, M.R., Kurniawan, Y. & Sidek, A.H. 2014 The impact of low, average, and high IQ on economic growth and technological progress: Do all individuals contribute equally? *Intelligence* **46**, 1-8.
- [169] Silvia, P.J., Nusbaum, E.C., Berg, C., Martin, C. & O'Connor, A. 2009 Openness to experience, plasticity, and creativity: Exploring lower-order, high-order, and interactive effects. *Journal of Research in Personality* **43**, 1087-1090.
- [170] Solomon, D. 2004 Questions for Stephen Hawking: The Science of Second-Guessing. In *The New York Times* (New York, NY, The New York Times).
- [171] Nisbett, R.E., Aronson, J., Blair, C., Dickens, W., Flynn, J., Halpern, D.F. & Turkheimer, E. 2012 Intelligence: new findings and theoretical developments. *American psychologist* **67**, 130.
- [172] Schmidt, F.L. & Hunter, J. 2004 General mental ability in the world of work: occupational attainment and job performance. *Journal of personality and social psychology* **86**, 162.
- [173] Joshi, P.K. & Esko, T. & Mattsson, H. & Eklund, N. & Gandin, I. & Natile, T. & Jackson, A.U. & Schurmann, C. & Smith, A.V. & Zhang, W., et al. 2015 Directional dominance on stature and cognition in diverse human populations. *Nature* **523**, 459-462.
- [174] Nisbett, R.E., Aronson, J., Blair, C., Dickens, W., Flynn, J., Halpern, D.F. & Turkheimer, E. 2012 Group differences in IQ are best understood as environmental in origin. *American psychologist* **67**, 503-504.

- [175] Lehman, D.R., Chiu, C.-y. & Schaller, M. 2004 Psychology and culture. *Annu. Rev. Psychol.* **55**, 689-714.
- [176] Postlethwaite, B.E. 2011 Fluid ability, crystallized ability, and performance across multiple domains: a meta-analysis. Iowa, University of Iowa.
- [177] Brinch, C.N. & Galloway, T.A. 2012 Schooling in adolescence raises IQ scores. *Proceedings of the National Academy of Sciences* **109**, 425-430.
- [178] Davis, H.E. 2014 Variable Education Exposure and Cognitive Task Performance among the Tsimane Forager-Horticulturalists [PhD Dissertation], The University of New Mexico.
- [179] Aghion, P., Boustan, L., Hoxby, C. & Vandenbussche, J. 2009 The causal impact of education on economic growth: evidence from US. In *Working Paper* (
- [180] Trahan, L.H., Stuebing, K.K., Fletcher, J.M. & Hiscock, M. 2014 The Flynn effect: A meta-analysis. *Psychological Bulletin* **140**, 1332-1360.
- [181] Pietschnig, J. & Voracek, M. 2015 One Century of Global IQ Gains: A Formal Meta-Analysis of the Flynn Effect (1909–2013). *Perspectives on Psychological Science* **10**, 282-306.
- [182] Wicherts, J.M., Borsboom, D. & Dolan, C.V. 2010 Why national IQs do not support evolutionary theories of intelligence. *Personality and Individual Differences* **48**, 91-96.
- [183] Inoue, S. & Matsuzawa, T. 2007 Working memory of numerals in chimpanzees. *Current Biology* **17**, R1004-R1005.
- [184] Klingberg, T. 2014 Childhood cognitive development as a skill. *Trends in Cognitive Sciences* **18**, 573-579.
- [185] Henrich, J., Boyd, R. & Richerson, P.J. 2012 The puzzle of monogamous marriage. *Philosophical Transactions of the Royal Society B: Biological Sciences* **367**, 657-669.
- [186] Gruber, T., Muller, M.N., Strimling, P., Wrangham, R. & Zuberbühler, K. 2009 Wild Chimpanzees Rely on Cultural Knowledge to Solve an Experimental Honey Acquisition Task. *Current Biology* **19**, 1806-1810.
- [187] Gruber, T., Muller, M.N., Reynolds, V., Wrangham, R. & Zuberbühler, K. 2011 Community-specific evaluation of tool affordances in wild chimpanzees. *Scientific Reports* **1**.
- [188] Chang, Y., Li, B.-D., Chen, H.-C. & Chiu, F.-C. 2014 Investigating the synergy of critical thinking and creative thinking in the course of integrated activity in Taiwan. *Educational Psychology* **35**, 341-360.
- [189] Nyberg, L., Sandblom, J., Jones, S., Neely, A.S., Petersson, K.M., Ingvar, M. & Bäckman, L. 2003 Neural correlates of training-related memory improvement in adulthood and aging. *Proceedings of the National Academy of Sciences of the United States of America* **100**, 13728-13733.
- [190] Jensen, M.S. & Finley, F.N. 1995 Teaching evolution using historical arguments in a conceptual change strategy. *Science Education* **79**, 147-166.
- [191] Nisbett, R.E., Peng, K., Choi, I. & Norenzayan, A. 2001 Culture and systems of thought: holistic versus analytic cognition. *Psychological review* **108**, 291.
- [192] Monga, A.B. & John, D.R. 2007 Cultural differences in brand extension evaluation: The influence of analytic versus holistic thinking. *Journal of Consumer Research* **33**, 529-536.
- [193] Miyamoto, Y., Nisbett, R.E. & Masuda, T. 2006 Culture and the Physical Environment: Holistic Versus Analytic Perceptual Affordances. *Psychological Science* **17**, 113-119.
- [194] Michel, J.-B., Shen, Y.K., Aiden, A.P., Veres, A., Gray, M.K., Pickett, J.P., Hoiberg, D., Clancy, D., Norvig, P. & Orwant, J. 2011 Quantitative analysis of culture using millions of digitized books. *science* **331**, 176-182.
- [195] Database of Religious History. 2015 Database of Religious History. (