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Supporting Online Material
www.sciencemag.org/cgi/content/full/335/6072/1110/DC1
Materials and Methods
Figs. S1 to S8
Tables S1 and S2
References (*24*–*40*)
Movies S1 and S2

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Identification of the Social and Cognitive Processes Underlying Human Cumulative Culture

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The remarkable ecological and demographic success of humanity is largely attributed to our capacity for cumulative culture, with knowledge and technology accumulating over time, yet the social and cognitive capabilities that have enabled cumulative culture remain unclear. In a comparative study of sequential problem solving, we provided groups of capuchin monkeys, chimpanzees, and children with an experimental puzzlebox that could be solved in three stages to retrieve rewards of increasing desirability. The success of the children, but not of the chimpanzees or capuchins, in reaching higher-level solutions was strongly associated with a package of sociocognitive processes—including teaching through verbal instruction, imitation, and prosociality—that were observed only in the children and covaried with performance.

The success of humanity in colonizing virtually every terrestrial habitat on the planet and resolving countless ecological, social, and technological challenges is widely attributed to our species' unique capability for "cumulative culture"—the extensive accumulation of knowledge, and iterative improvements in technology, over time (*1*, *2*). Although many animals—especially mammals, birds, and fishes—acquire knowledge and skills from others (often manifest in behavioral traditions), in no instance have these unambiguously exhibited "ratcheting" in complexity (*2*). Given that the adaptive value of cumulative learning is well established (*1*, *3*, *4*), the question as to why social learning is so much more widespread than cumulative culture constitutes a major evolutionary puzzle (*1*, *4*–*7*).

Although claims have been made for cumulative culture in other species (*8*–*10*), the evidence is circumstantial and contested (*2*, *5*, *6*, *11*). The resulting debate has spawned a large number of distinct hypotheses concerning the cognitive capabilities, or social conditions, thought to be necessary for cumulative culture. These explanations include a hypothesized critical dependency of cumulative culture on aspects of social cognition deemed to be exclusive to (or substantially enhanced in) humans, including teaching (henceforth hypothesis 1, or *H1*), language (*H2*), imitation (*H3*), and prosociality (*H4*) (*1*, *2*, *4*, *5*, *11*–*14*). Other explanations stress features of social structure that mitigate against the spread of superior solutions in animals other than humans, including scrounging (kleptoparasitism; *H5*), which can hinder social learning and demotivate resource production (*15*); the tendency of dominant individuals to monopolize resources, thereby preventing subordinates from learning (*H6*) (*16*); and a lack of attention to low-status inventors (*H7*) (*17*, *18*). A further (nonsocial cognition) hypothesis is that satisficing, or conservative behavior, hinders ratcheting in nonhumans (*H8*) (*8*, *19*). Large social networks (*20*, *21*) may enhance cultural diversity and promote cumulative culture, but we do not consider this hypothesis because it presupposes the existence of the necessary cognitive capabilities.

Cumulative culture has been investigated through historical analysis (*22*), in the psychological laboratory (*23*), and through experimentation in chimpanzees (*14*). However, until now, there has been no extensive and rigorous experimental investigation of the capacity for cumulative cultural learning that simultaneously tests humans and other animals using the same apparatus and that is capable of evaluating all of the aforementioned hypotheses. Here, we present such an investigation.

We designed a puzzlebox (Fig. 1) that could be solved at three stages of difficulty, with success at stage 2 building on stage 1 and success at stage 3 building on stage 2. We presented appropriately scaled versions, under a variety of conditions, to groups of children ($N = 35$, eight groups of 3- to 4-year-olds from three nurseries in Fife, UK), chimpanzees (*Pan troglodytes*; $N = 74$, eight mixed juvenile and adult groups at the Michale E. Keeling Center for Comparative Medicine and Research, University of Texas), and capuchin monkeys (*Cebus apella*; one group over 2 years, year 1 $N = 22$, year 2 $N = 18$, at the Centre de Primatologie, Strasbourg) (see supporting online material). All stages could be completed through two parallel options (Fig. 1), allowing us to investigate cooperation, tolerance, and social learning at the task; presentation in social groups allowed solutions to each level to spread among individuals. Experiment 1 included two conditions: an "open" condition, where groups could gain access to all stages and a "scaffolded" condition, where guards prevented access to the manipulandi associated with higher stages until performance at the lower stage reached criterion. In experiment 2, conducted only with chimpanzees, one female from each of four additional groups was isolated from her group and trained to use the puzzlebox to stage 3. The use of trained females of differing status as demonstrators allowed investigation of how social rank affected the spread of solutions.

Chimpanzees and capuchins were selected because the evidence for cultural traditions is as strong in these species as in any nonhuman (*24*, *25*), maximizing the chances of observing cumulative cultural learning. Moreover, chimpanzees, as our closest relative, provide an appropriate comparator to humans, with the performance of capuchins aiding interpretation of any chimpanzee-human differences. Children are widely used in comparative studies [e.g., (*26*)] to help tease out the effects of culture, as adults have been greatly enculturated by society.

We anticipated that children, but not chimpanzees or capuchins, would exhibit evidence of cumulative cultural learning, and the study was designed to sort between alternative explanations

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for this. For a hypothesis to be deemed supported (i.e., not falsified), we specified that it should satisfy two criteria: (i) Differences in the relevant predictor variable should covary with differences in species' mean performance in the cumulative task, in the predicted direction; and (ii) within-species variation in the relevant predictor should covary with variation in individual performance within species, in the predicted direction. Thus, we used analyses of covariation, both between and within species, to reject causal hypotheses that were inconsistent with the data. We further assumed that the manner in which social or cognitive processes currently operate is qualitatively similar to the manner in which they operated in ancestral environments. Hence, although our study sought to identify the proximate processes underlying cumulative cultural learning in contemporary populations, the same processes were potentially ancestral sources of selection.

Performance with the puzzlebox is summarized in Fig. 2A. After 30 hours of presentation of the task to each of four chimpanzee groups, only 1 of 33 individuals reached stage 3, with a further 4 having reached stage 2, and with each group having witnessed multiple solvers at stage 1 (experiment 1). Chimpanzee performance was not greatly enhanced by trained demonstrators (experiment 2), who performed stages 1 to 3 proficiently. A similar pattern was observed in the capuchins: After 53 hours, no individual reached stage 3 and only two individuals reached stage 2. Thus, the experiments provide no evidence for cumulative cultural learning in chimpanzees or capuchins. These findings stand in stark contrast to those of the children, where despite a far shorter exposure to the apparatus (2.5 hours), five of the eight groups had at least two individuals (out of a maximum of five) who reached stage 3, with multiple solvers at stages 2 or 3 in all but two groups (see supporting online material).

Analyses revealed support for four of the eight hypotheses (Fig. 2, B to E), suggesting that teaching, communication, observational learning, and prosociality all played important roles in human cultural learning but were absent (or played an impoverished role) in the learning of chimpanzees and capuchins.

A total of 23 unambiguous instances of teaching by direct instruction (i.e., referencing part of the puzzlebox) were observed ($\bar{x} = 0.69 \pm 0.32$), exclusively in the children (*H1*) (Fig. 2B), of which all involved task-relevant communication (e.g., "push that button there") and approximately one-third involved gesture. A strong positive relationship was observed between the amount of instruction received and the stage reached by a child [Spearman's $\rho = 0.598$, $P = 0.0001$ (*27*)]. Such an analysis fails to consider teaching precursors, or subtle processes similar to teaching, such as "pedagogical cuing" (*28*) or "scaffolding" (*29*). To explore whether chimpanzees or capuchins might facilitate learning in others (e.g., through enlisting offspring's interest in the task), we examined rates of both provisioning and food-calling by "knowledgeable" individuals. However, we observed substantially greater rates of tolerated theft of extracted food by mothers from offspring than vice versa in chimpanzees (Wilcoxon $W = 16$, $P = 0.026$) and no tolerated theft in mother-infant pairs of capuchins. Moreover, neither chimpanzees (Wilcoxon $W = 6.5$, $P = 0.77$) nor capuchins ($W = 9$, $P = 0.45$) exhibited any difference in the rate of recruitment of others to the puzzlebox before, versus immediately after, a food call, and low rates of calling were observed; in contrast, children who received verbal instruction outperformed those who did not (*H2*) (Mann-Whitney $U = 41$, $P = 0.002$; Fig. 2C).

We also compared the rate at which individuals from each species, in their first response or during the subsequent minute, performed a matching manipulation (e.g., copy push down button on left) to that observed being performed by another individual departing the box (*H3*). Matching (table S6) could constitute copying the actions of others (i.e., imitation) or making the same manipulandi move in the same way (i.e., emulation). Children alone performed more matching than nonmatching manipulations (Wilcoxon $W = 163$, $P = 0.003$), they produced a significantly greater proportion of matching actions than both chimpanzees and capuchins (Kruskal-Wallis $\chi^2 = 18.13$, df = 2, $P = 0.001$; Fig. 2D), and the degree of matching they exhibited correlated positively with performance (Spearman's $\rho = 0.41$, $P = 0.01$). We observed chimpanzee social learning at stage 1 (option-bias analysis, $\chi^2 = 941.6$, $P = 0.021$) (*30*) but not at higher stages.

Regarding prosociality (*H4*), we hypothesized that if individuals voluntarily give rewards to others, this signifies an understanding that others share the motivation of achieving the goal that they had achieved. We observed 215 altruistic events where a child spontaneously gave another child a retrieved reward ($\bar{x} = 6.14 \pm 2.32$; 47% of children exhibited altruism), but not a single instance of the voluntary donation of food in either the chimpanzees or capuchins (Fig. 2E). The number of prosocial acts received covaried strongly with the stage that a child reached (Spearman's $\rho = 0.54$, $P = 0.001$). Moreover, the proportion of manipulations that children performed at the same time that another individual was in proximity was significantly greater than in either chimpanzees or capuchins, indicating greater tolerance of others, cooperation, and shared motivation among children.

The other four hypotheses failed to satisfy our criteria, providing little evidence that the capability for cumulative culture is affected by either social structure or nonsocial cognition. There was a positive, rather than the predicted negative, correlation between the amount of

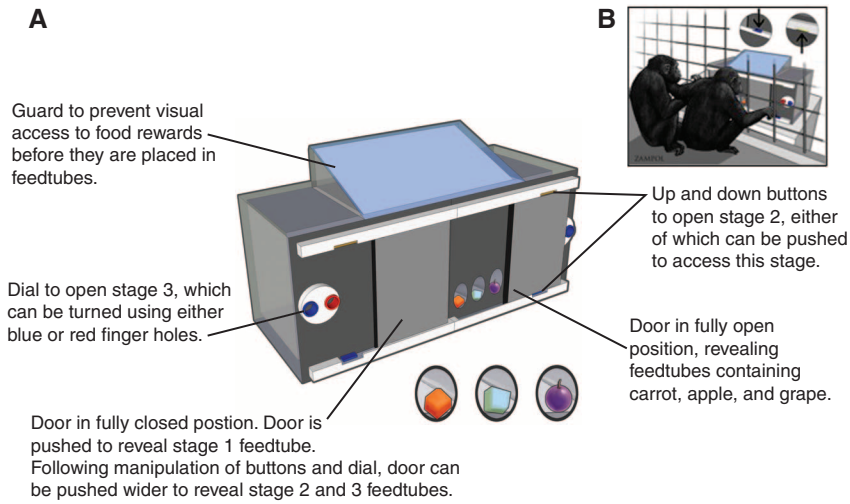

Fig. 1. (**A**). The cumulative culture puzzlebox, which could be solved at three sequential stages, each building on the preceding stage. (**B**) Illustration of puzzlebox use. Stage 1 required individuals to push a door in the horizontal plane to reveal a chute through which a low-grade reward was delivered. Stage 2 required individuals to depress a button and slide the door further to reveal a second chute for a medium-grade reward. Stage 3 required the solver to rotate a dial, releasing the door to slide still further to reveal a third chute containing a high-grade reward. All stages could be completed through two parallel options (alternative doors could be slid left or right at stage 1, alternative buttons at the top or bottom could be depressed at stage 2, and alternative colored finger holes enabled rotation of the dial at stage 3), with sets of three chutes on both left and right sides. This two-action, two-option design aided evaluation of alternative social learning mechanisms and allowed two individuals to operate the puzzlebox simultaneously. Replenishment of the chutes by the experimenter allowed the apparatus to be continuously used for long periods. Pilot work established an unambiguous ascendancy in the desirability of reward with stage (food stage 1 = carrot, 2 = apple, 3 = grapes for chimpanzees and capuchins; stickers of increasing size and attractiveness for children).

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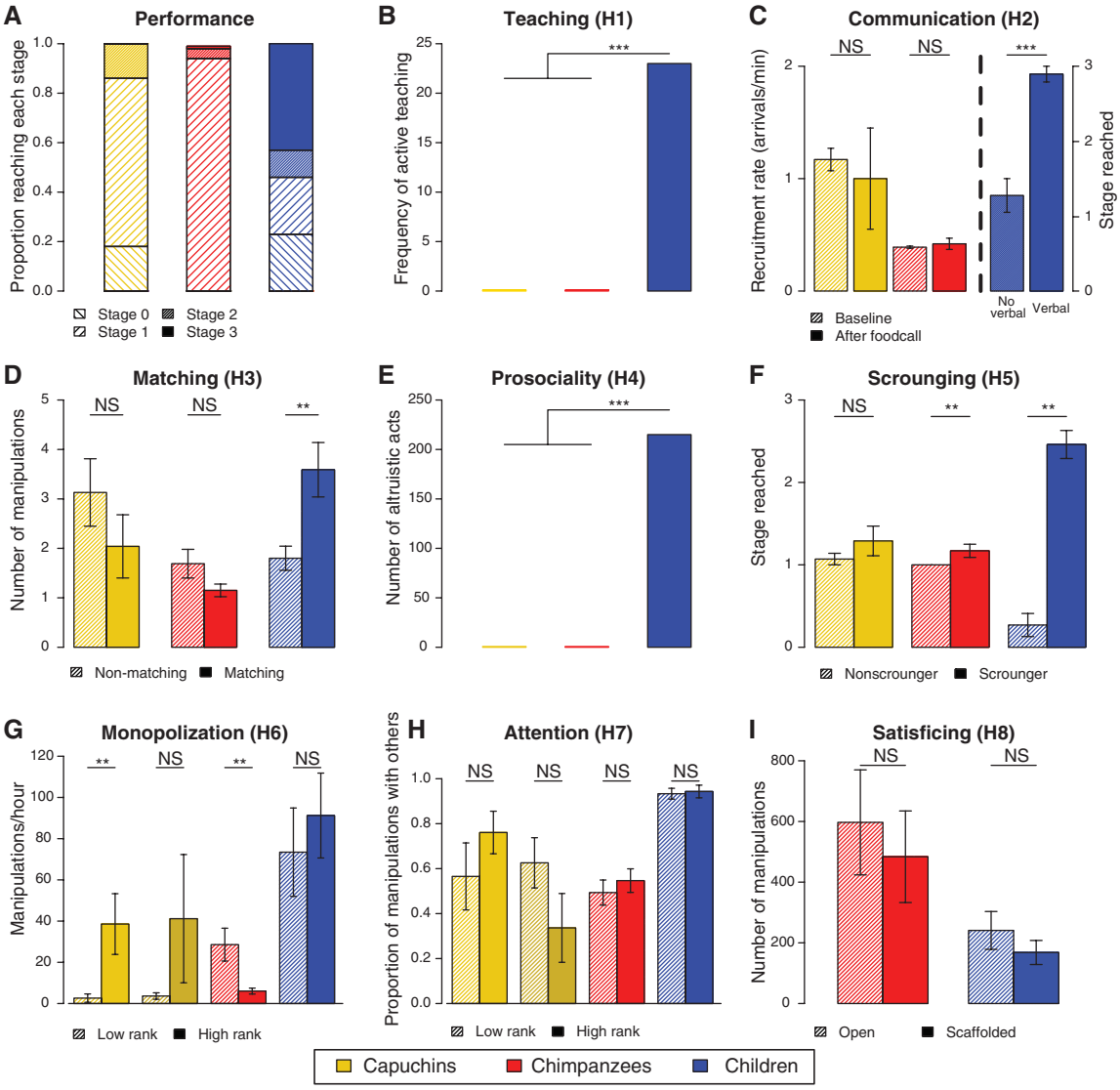

Fig. 2. (**A**) Attainment of stages 2 and 3 was exceptionally rare or absent in capuchins and chimpanzees but common in human children. (**B**) We observed 23 unambiguous instances of teaching, by direct instruction, exclusively in children. (**C**) In neither chimpanzees nor capuchins was there greater recruitment to the task after, versus before, a food call. Conversely, children who received verbal instruction outperformed those who did not. (**D**) Children alone performed more matching than nonmatching manipulations, and they produced a greater proportion of matching actions than did either chimpanzees or capuchins. (**E**) We observed 215 altruistic events (giving an extracted reward to others), exclusively in children. (**F**) There was no evidence that scrounging hindered performance in any species; children who were victims of scrounging outperformed children who were not. (**G**) Dominant children and chimpanzees did not monopolize the task, and high-ranking capuchins monopolized the puzzlebox in 2007 but not 2008. (**H**) Low-rankers did not receive less attention than high-rankers when manipulating the task. (**I**) In the open condition, where they received rewards at all stages, neither chimpanzees nor children manipulated the puzzlebox less than individuals in the scaffolded condition. In (G) and (H), capuchins (2007 and 2008 pale and dark yellow, respectively) and chimpanzees were split into three (high-, mid-, low-) rank categories, although for clarity and comparability with the child data, we present only analysis of high- versus low-ranked individuals. $^{**}P \leq 0.05$; $^{***}P \leq 0.01$; NS, not significant.

Table 1. Numbers (and percentages) of children reaching each stage, together with the amount of teaching, matching (e.g., imitation), and prosociality (altruism) exhibited.

Stage reached	Number of individuals (from *N* groups)	Number that received teaching	Number with more matching than nonmatching manipulations	Number that received altruism	Number that received no social support
0	8 (5)	0	1 (12.5%)	0	7 (87.5%)
1	8 (3)	0	4 (50%)	4 (50%)	3 (37.5%)
2	4 (3)	1 (25%)	1 (25%)	2 (50%)	1 (25%)
3	15 (5)	9 (60%)	11 (73%)	11 (73%)	0

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scrounging an individual falls victim to and performance in capuchins (Spearman's $\rho = 0.71$, $P = 0.0002$), chimpanzees ($\rho = 0.312$, $P = 0.008$), and children ($\rho = 0.8$, $P = 6.87 \times 10^{-9}$), and no sign that scrounging hindered performance (*H5*) (Fig. 2F). Dominant children (Wilcoxon $W = 186$, $P = 0.15$) and chimpanzees [analysis of variance (ANOVA) $F_{2,72} = 3.49$, $P = 0.036$] did not monopolize the puzzlebox (*H6*), and although there was a positive correlation between rank and puzzlebox use among capuchins in 2007 (Kruskal-Wallis $\chi^2 = 8.23$, df = 2, $P = 0.016$), this was not repeated in 2008 ($\chi^2 = 0.13$, df = 2, $P = 0.93$) (Fig. 2G). When manipulating the box, low-rankers did not receive less attention (defined as having others within 1.5 m of the task) than high-rankers (*H7*) (Fig. 2H; capuchins 2007, Kruskal-Wallis $\chi^2 = 2.49$, df = 2, $P = 0.29$; capuchins 2008, $\chi^2 = 2.08$, df = 2, $P = 0.35$; chimpanzees, ANOVA $F_{2,72} = 1.22$, $P = 0.3$; children, Wilcoxon $W = 100$, $P = 0.61$), nor was there any evidence for satisficing or conservatism (*H8*) (Fig. 2I; chimpanzees, Mann-Whitney $U = 166.5$, $P = 0.42$; children, $U = 163$, $P = 0.54$), with individuals continuing to manipulate the dials and buttons of the puzzlebox after they had found the solution to stage 1. In the open condition, where they received rewards at all stages, both chimpanzees and children manipulated the puzzlebox slightly more, rather than less, than individuals in the scaffolded condition, despite the latter being unrewarded at the previous stage(s). Although we did not find a significant difference between the proportions of rewards scrounged at each stage in chimpanzees, they expressed clear and strong preferences for the three foodstuffs in pilot work, and olfactory holes in the doors allowed these foods to be detected in the apparatus prior to their extraction. Moreover, many of the chimpanzees performed failed attempts to access the foods by "termiting" (inserting stalks through the olfactory holes), and all 29 cases involved an attempt to reach the highest-stage food that was available. In the children and capuchins, more low-stage than high-stage rewards were scrounged, which reflects a greater motivation to retain high-grade rewards.

Thus, we found no support for the hypotheses that cumulative culture is absent in chimpanzees or capuchins because in these species the social transmission of superior solutions is hindered by scrounging, because dominant individuals monopolize key resources, because of a lack of attention to low-status innovators, because these animals satisfice, or because these animals were unable to discriminate higher-quality from lower-quality rewards. Nor can the results be easily dismissed as an artifact of captivity testing, as wild chimpanzees and capuchins have been subjected to long-term studies that reveal no unambiguous evidence for cumulative culture (*24*, *25*). Likewise, our animals cannot be described as "dysfunctional" because they have performed effectively in previous studies demonstrating social learning and tradition of noncumulative tasks (*31*, *32*).

Closer inspection of the children's behavior supports the conclusion that a package of social cognitive capabilities, encompassing teaching (largely through verbal instruction) as well as matching (e.g., imitation) and prosociality (altruism), was critical for performance at the highest level. Table 1 reveals that all children who reached level 3 received at least one form of social support and 86% received at least two types. Conversely, children who did not benefit from social support generally performed poorly in the task. These data not only provide clear and strong evidence for a cumulative cultural capability in the children but strongly link their elevated performance to their social cognition.

The puzzlebox experiment reveals clear and characteristic differences in cumulative cultural learning and patterns of social interaction among children, chimpanzees, and capuchin monkeys, highlighting sociocognitive processes that may be important for cultural transmission to "ratchet." The children responded to the apparatus as a social exercise, manipulating the box together, matching the actions of others, facilitating learning in others through verbal instruction and gesture, and engaging in repeated prosocial acts of spontaneous gifts of the rewards they themselves retrieved. In contrast, the chimpanzees and capuchins appeared to interact with the apparatus solely as a means to procure resources for themselves, in an entirely self-serving manner, largely independent of the performance of others, and exhibiting restricted learning that appeared primarily asocial in character.

Our findings, based on confirmation of predicted patterns of covariation both between and within species, constitute strong support for the view (*2*, *11*, *12*) that cumulative culture requires a package of key psychological processes—specifically, teaching through verbal instruction, imitation, and prosocial tendencies—that are present in humans but are absent or impoverished in chimpanzees and capuchins. The claim that these sociocognitive processes, rather than other effects, were directly responsible for the pattern of cumulative cultural learning observed in the children is supported by the positive relationships found between the stage reached and the amount of teaching, verbal instruction, and prosocial acts received, as well as between the stage reached and the amount of observational learning that took place (Table 1).

We reject as improbable the alternative causal hypotheses that performing well in the task caused elevated levels of the predictor variables or that some unspecified factor elevated both performance and the predictors. It is not clear why success in solving the task should cause children to imitate, be taught by, or receive rewards from others, nor how an unspecified third variable might account for our within-species data. For instance, although it is possible that the relationship between imitation and performance reflects the child's cognitive ability, this explanation cannot account for the relationships of both teaching and prosociality with performance, because in both cases the donor (of knowledge or reward) is a different individual from the learner. The most likely explanation is that aspects of human social cognition are directly responsible for the cumulative culture capability.

Human cultural traditions accumulate refinements over time, thereby producing both technology and other cultural achievements of astonishing complexity and diversity unprecedented in the rest of nature. Although numerous hypotheses have been proposed for this phenomenon, the explanation has for many years remained elusive. Our experiment provides a clear answer to this conundrum, providing strong support for the position advanced by Tomasello and colleagues (*2*, *11*, *12*, *33*) that "human social learners focus to a much greater degree than other nonhuman primates on the actual actions performed by others …[and]… that uniquely human forms of cooperation ... teaching and norms of conformity contribute to the cultural ratchet" [(*11*), p. 2413]. These findings pave the way for an exciting avenue of research into when and why this particular "package" of other-regarding sociocognitive capacities evolved.

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Supporting Online Material
www.sciencemag.org/cgi/content/full/335/6072/1114/DC1
Materials and Methods
Figs. S1 and S2
Tables S1 to S6

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The Effects of Experience and Attrition for Novice High-School Science and Mathematics Teachers

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Because of the current high proportion of novice high-school teachers, many students' mastery of science and mathematics depends on the effectiveness of early-career teachers. In this study, which used value-added models to analyze high-school teachers' effectiveness in raising test scores on 1.05 million end-of-course exams, we found that the effectiveness of high-school science and mathematics teachers increased substantially with experience but exhibited diminishing rates of return by their fourth year; that teachers of algebra 1, algebra 2, biology, and physical science who continued to teach for at least 5 years were more effective as novice teachers than those who left the profession earlier; and that novice teachers of physics, chemistry, physical science, geometry, and biology exhibited steeper growth in effectiveness than did novice non–science, technology, engineering, and mathematics teachers.

In the past two decades, the teacher labor market has dramatically changed in response to more employment opportunities for women, increased demand for teachers, and policies opening new pathways into the profession (*1*). For instance, the modal value of experience for U.S. teachers dropped from 15 years in 1987–1988 to 1 year in 2007–2008 (*2*). Additionally, turnover for beginning teachers is high: After just 5 years, nearly 50% of all novice teachers have exited the profession (*3*). This churn of beginning teachers in and out of public schools results in more students, particularly poor and/or ethnic minority students, being taught by novice teachers (*4*, *5*), and that in turn leads to reduced student achievement (*6*–*11*). Investigating the consequences of these teacher labor market conditions for high-school students' science and mathematics achievement—specifically, the effects of experience and attrition among novice teachers—will shed light on challenges facing education and career preparation in science and mathematics.

We quantified the growth in effectiveness of high-school science and mathematics teachers and the effects of those teachers who exit public school classrooms. We analyzed effectiveness using scores on standardized tests given to high-school students in three mathematics courses and four science courses. We define teachers' effectiveness in terms of the increases in their students' test scores, adjusted for the prior achievement of the individual students and for other student, classroom, and school covariates. Prior research shows that the average effectiveness of novice teachers increases during their first 3 years and flattens thereafter (*12*–*14*); and that after differences in effectiveness that are attributable to experience are removed, less effective teachers are more likely to exit the profession (*10*, *15*, *16*). We extended this research to investigate teacher effectiveness in specific high-school courses and addressed three questions: (i) To what extent do novice high-school science and mathematics teachers become more effective with additional experience? (ii) Are novice high-school science and mathematics teachers who exit public schools more or less effective than those who stay? [There is little published research on where teachers who exit public schools are subsequently employed, but it suggests that leaving for higher-paying jobs in the private sector is relatively rare (*17*).] (iii) Do the rates of change in effectiveness for high-school science and mathematics teachers vary by course?

Student outcomes are related to variations in many school-related factors, including leadership; an orderly environment; high student expectations; a focus on student outcomes; a positive school culture; parental involvement; and, most closely, to teachers' effectiveness (*18*, *19*). Teachers are the most important school-related variable explaining variation in student achievement (*12*, *18*, *20*), and teacher experience positively affects student performance (*6*–*11*). Most gains in effectiveness occur in the first 3 years of teachers' careers, with minimal increases thereafter (*13*).

It is likely that through teaching experience, trial and error, professional development, mentoring, and/or collaboration with fellow educators, teachers learn rapidly during their first few years on the job. However, some of the average increases in effectiveness that have been attributed to experience may be a statistical artifact caused by the exit of less effective early-career teachers, thereby overstating the year-to-year differences in the statistics related to experience. Recent research supports this second explanation, finding that exiting teachers are less effective than comparable teachers who remain in the profession (*10*, *15*, *16*). Here we disentangle the effects of teacher development from differential attrition among high-school teachers of science and mathematics courses.

To assess the effectiveness and attrition of novice science and mathematics teachers, we developed a data set from North Carolina containing end-of-course test scores for seven science and mathematics courses—algebra 1, algebra 2, geometry, biology, chemistry, physical science, and physics—and three other courses—English 1, U.S. history, and civics/economics—which we grouped together for the purposes of our analysis and label non-STEM (science, technology, engineering, and mathematics) courses. Our study sample included all teachers in tested subjects with less than 5 years of experience employed in any regular North Carolina public high school from 2005–2006 through 2009–2010. The most crucial feature of the data set is that students and teachers were linked on the basis of actual classroom rosters, which allowed us to match approx-

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Identification of the Social and Cognitive Processes Underlying Human Cumulative Culture

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Acquire and Share

Few would argue with the stance that human social cognition supports an unequaled capacity to acquire knowledge and to share it with others. **Dean *et al.*** (p. 1114; see the Perspective by **Kurzban and Barrett**) compared the extent to which these social and cognitive psychological processes can be elicited in children, capuchins, and chimpanzees through the use of a three-level puzzlebox task. Incentivized by improving rewards, 3- to 4-year-old children progressed from the first to the third level by imitating observed actions, taught other members of their social group how to solve the problem, and shared the rewards obtained. By contrast, neither the capuchins nor chimpanzees, very few of which ever reached the third level, exhibited these charactertistics.

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