Assessor teaching and the development of the capacity to innovate and to imitate

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ABSTRACT

Human beings have generated a system of cumulative cultural learning with great adaptive value. The evolution of this system required an increase in the capacity to innovate and to imitate in hominin lineage. However that development is costly and, moreover, imitation may restrain the adaptive advantage of a greater investment on innovation. We suggest that a possible way to overcome this problem in hominin evolution was parental teaching by evaluative feedback - i.e. assessor teaching. To explore this hypothesis we developed a mathematical model of cumulative cultural learning. We consider two cognitive levels, one Basic, with less ability to imitate and innovate, and the other Smart, with more ability of both. We study the transition from Basic to Smart in the absence or in presence of teaching. We also study the transition from no teaching to teaching at each cognitive level. We show that the transition to a Smart is easier in a teaching context than in one of only imitation. We also show that the transition to teaching is easier the greater the cognitive level.

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1. Introduction

Social learning, and even cultural traditions, is present in some species of primates (Whiten et al., 1999). However, social learning is nowhere as important in any other species as it is in humans, where it led to a cumulative cultural evolution process with great adaptive value (Boyd and Richerson, 1985; Tomasello, 1999; Richerson and Boyd, 2005; Enquist and Ghirlanda, 2007; Hill et al., 2009; Tennie et al., 2009; Mesoudi, 2011; Henrich, 2015). The capacity of human culture to accumulate ever more effective solutions through repeated bouts of innovation and social transmission, led to the evolution of technological achievements of astonishing complexity that no individual could alone invent. It seems reasonable to assume that sooner or later the growing complexity of some cultural traits also introduces frequent errors in imitation and, therefore, the process of cumulative cultural evolution would be affected (Ehn and Laland, 2012; Castro and Toro, 2012; 2014). Therefore, it seems that high-fidelity cultural transmission is necessary for cumulative culture to attain refinements (Fogarty et al., 2011; Lewis and Laland, 2012; Morgan et al., 2015; Gärdenfors and Högberg, 2017).

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The cognitive capabilities that have enabled cumulative culture remain unclear (Dean et al., 2012), yet it is considered that the coupling of innovation and imitation is essential for the development of cumulative cultural learning (Henrich and McElreath, 2003; Richerson and Boyd, 2005). There is consensus that both innovation and imitation coevolved in the hominin lineage (Reader et al., 2011; Navarrete et al., 2016). The development of these abilities seems to require further development of the brain and, most probably, a longer individual ontogenetic period (Deaner et al., 2003; Barrickman, 2008). There is evidence that a larger brain size relative to body size is correlated in primates with social learning abilities (i.e., imitation), as well as individual learning (i.e., innovation) and tool use, all three of which are highly inter-correlated (Reader and Laland, 2002; Reader et al., 2011; for a review see Shultz et al., 2012). However, innovation can favor the development of imitation, while the development of the latter does not necessarily generate a positive feedback process to favor the former (Aoki, 2001; Henrich and McElreath, 2003). Those individuals who imitate gain access to behavioral innovations from individuals with a higher intellectual capacity, not necessarily their parents, and therefore, imitation may restrain the adaptive advantage of a greater investment on innovation -i.e., there may be an evolutionary trade-off between imitation and innovation.

A possible way to overcome this trade-off is parental teaching by evaluative feedback -i.e., assessor teaching (Castro and Toro,

2004; 2014). Parental evaluative feedback facilitates the replication and reconstruction of behaviors that are difficult to imitate and it can be considered an elementary type of teaching that aims to facilitate learning in another (Castro and Toro, 2004; Kline, 2015). Fogarty et al. (2011) have proposed that teaching and cumulative culture reinforce each other, and may have coevolved, because teaching is more advantageous in a cumulative culture. This is consistent with recent theories suggest that early forms of teaching in humans must be universal (Castro and Toro, 2004; Csibra and Gergely, 2006; Tehrani and Riede, 2008; Gergely and Csibra, 2011; Strauss and Ziv, 2012; Kline, 2015; Hewlett and Roulette, 2016; Gärdenfors, 2017). Furthermore, cognitive growth in hominin species was established at the expense of prolonging ontogenetic development (Barrickman, 2008) and teaching by evaluative feedback could be necessary to care and to protect offspring in a collective manner (Hrdy, 2009). Once emerged, elementary forms of parent-child education can foster greater innovation capacity because the behaviors are preferentially transmitted from innovator parents to their children. Additionally, adaptive complex behavior can also improve the imitation ability to take advantage of the lessons learned by other individuals, not the parents. In summary, teaching could stimulate the development of higher capacity to innovate and to imitate.

Almost certainly, the first species of the genus *Homo* had the ability to imitate and a theory of mind (Dunbar 1996). Our hypothesis is that the step for the development of teaching by evaluative feedback did not require a huge cognitive leap in hominin species. We suggest that assessor teaching came early in the hominin evolution. This is consistent with the thesis that some authors defend that the Acheulean hand-axe technology requires for high-fidelity mechanisms of social learning (Högberg et al., 2015; Morgan et al., 2015; Gärdenfors and Högberg, 2017; Di Paolo and Di Vincenzo, 2018; Shipton and Nielsen, 2018; but see, for a different opinion, Tennie et al., 2016).

In this essay, we want to explore the role of parental teaching by evaluative feedback (assessor teaching) in such evolutionary scenario. For this, we have developed a model of cumulative cultural learning. We consider two cognitive levels, one Basic, with less ability to imitate and innovate, and the other Smart, with more ability of both and with a cost derived from a greater period of ontogeny. We study the transition from no teaching to teaching at each cognitive level, Basic and Smart. We also study the transition from Basic to Smart in the absence or in presence of teaching. From this model, we show first that the transition from no teaching to teaching is easier the greater the cognitive capacity of individuals -i.e., when individuals are Smart. Second, we show that the transition from Basic to Smart is easier in presence of teaching, because the adaptive advantage that provides to be Smart is greater in the context of teaching than in one of only imitation. Finally, we argue that elementary forms of parental teaching (assessor teaching) could emerge early in hominin evolution, driving the intellectual development of *Homo* species.

2. The simulation model

We designed our simulation model along the lines described by Rendell et al. (2010) and by our previous work to perform a competition between cultural learning strategies (Castro and Toro, 2014). Each individual acquires a behavior *A* having in turn 10 levels of complexity ($A_1 \dots A_{10}$). Each level represents a progressive accumulation of complexity in that behavior. Individual fitness is a function of the baseline payoff (p_0). Payoffs for the different levels of this behavior A_i were constructed so that the payoff p_i of level i was equal to $p_i = p_0 + i\alpha$, where p_0 is a basal payoff of an individual that does not exploit the conduct *A* and α is a factor that allowed to scale the intensity of the rising payoff as the

level changed. We consider $p_0 = 100$, and $\alpha = 2$ in standard conditions. Thus an individual with level $i = 10$ has a payoff of 120 and one with level $i = 1$ of 102. These values imply a moderate linear increase of the payoff.

Each simulation contained a population of 100 agents. At the start of the play, all possess the level 1 of the conduct *A*. Each agent can increase this level through learning. We consider two types of social learning (parental imitation and partner imitation), and one kind of asocial learning (innovation). We assumed that the higher is the level of complexity more difficult is to imitate and refine. In the first round, each agent mimics the behavior A_i of his father and reproduces it with probability $h_i = h/i$, whereas with probability $1 - h_i$, it obtains level 1 of that behavior (A_1). In the second round, a random partner is used ($A_{i'}$). If the i' level of partner's conduct is higher than his own behavior after the first round, there is a probability $h_{i'} = h/(i' - i)$ to move up to i' level from the current one. If the i' level of conduct is equal to or lower than the level i that he currently has ($i' \leq i$), he does not change its level. In the third movement, the individual innovates by increasing level A_i behavior acquired in the first two rounds with probability $k_{i+1} = k/(i+1)$, while if he is unable to innovate, he maintains the previous behavior with probability $1 - k_{i+1}$. Then, from the fourth round, the individual tries to exploit the behavior he has learned playing Exploit. Exploit represents the performance of the behavior A_i that has developed the individual.

We consider four types of strategies, two without teaching ability, Basic (B) and Smart (S), and two with teaching ability, assessor Basic (a-B) and assessor Smart (a-S). We assume that offspring inherited their parent's strategy. Table 1 summarizes the characteristics that define each strategy. B and S strategies differ in their competence when imitating (h_i) or innovating (k_{i+1}) and the number of rounds during the period of childhood. Each individual has a childhood ontogenetic period during which he cannot be parent and fails to exploit successfully learned behavior -i.e., he did not collect benefits. The period of childhood contains 5 rounds for strategies B and a-B (the first 3 rounds of learning plus 2 rounds of play Exploit unsuccessfully), and 6 rounds (3 + 3) for the smartest strategies S and a-S. The strategy B mimics with probability $h_i = 0.6/i$, innovates with probability $k_{i+1} = 0.3$, and has a period of 5 rounds childhood. Meanwhile, the S strategy imitates and innovates better ($h_i = 0.8/i$; $k_{i+1} = 0.5$) but in return has a longer childhood (6 rounds), during which individuals cannot be parents and fail to exploit learned behavior. Strategies assessor a-B and a-S are equal respectively to B and S strategies but have teaching ability which we assume improves the efficiency of how children imitate. As a result, the child learns the behavior exhibited by the father with a probability hi constant and independent of the level of parental behavior ($h_i = 0.6$ for a-B and $h_i = 0.8$ for a-S). For parent a-B, the cost of assessor teaching is equivalent to a one round without play Exploit. For parents a-S, the cost of teaching is equivalent to a two rounds without playing Exploit as consequence of a slower ontogenetic development of the children. At any one time, every individual has a mean lifetime payoff calculated as the sum of the payoffs in each round, divided by the number of simulation rounds while alive. In the computation we included the period of childhood (5 rounds for strategies B and a-B or 6 rounds for strategies S and a-S) and the rounds of parental guidance when individuals are parents (one for strategy a-B or two for strategy a-S). In each of those rounds, agents earn only the basal payoff 100.

Evolutionary dynamics were realized by a death-birth process. Agents died with a constant probability of 1/50 per round and were replaced by the offspring of another agent. Thus, the average life of an individual is close to 50 rounds and the ontogenetic period represents about 10% of the average life -i.e., 5 rounds for the Basic strategies B and a-B, and 6 for the Smart strategies S and a-S. The probability that an agent was chosen to reproduce was propor-

Table 1
Parameters of each strategy (for cultural level i).

Parameters	Basic (B)	Smart (S)	Assessor Basic (a-B)	Assessor Smart (a-S)
Probability of parental imitation	$h_i = 0.6/i$	$h_i = 0.8/i$	$h_i = 0.6$	$h_i = 0.8$
Probability of partner imitation	$h_i' = 0.6/(i' - i)$	$h_i' = 0.8/(i' - i)$	$h_i' = 0.6/(i' - i)$	$h_i' = 0.8/(i' - i)$
Probability of innovation	$k_{i+1} = 0.3$	$k_{i+1} = 0.5$	$k_{i+1} = 0.3$	$k_{i+1} = 0.5$
Period of childhood	5 rounds	6 rounds	5 rounds	6 rounds
Cost of teaching	0 rounds	0 rounds	1 rounds	2 rounds

Table 2
Standard conditions of the simulation.

Population size	100
Number of cumulative cultural levels (i)	10
Probability of individual death	0.02
Basal payoff (p_0)	100
The increase of payoff for level (α)	$\alpha = 2$
Payoff p_i for cultural level i	$p_i = p_0 + i \alpha = 100 + 2i$
Probability of mutation in single contest	0.0
Probability of mutation in pairwise contest	0.001
Number of rounds	100000
Number of replicates	100

tional to its mean lifetime payoff. However, notice that agents cannot be chosen as parents during the childhood period. Therefore, the Smart individuals (S and a-S) have one extra round in which they cannot be parents. This is the most important cost of being a Smart strategy.

We analyzed the dynamics of each strategy when it occurs alone, when competing with others in pairwise contests, and when they all compete together. Offspring inherited their parent's strategy unless there was a mutation, in which case the offspring was given another strategy played in that simulation. The mutation rate used was 0.001 in pairwise contest. This high rate does not qualitatively affect the outcomes but decreases drift and offers significant computational advantages in terms of time to equilibrium. To analyze the dynamics of a population consisting of a single strategy we consider a mutation rate 0. Each pairwise contest (e.g., strategies 1 vs. 2) consisted of 100 simulations in which agents performing the second strategy were introduced by mutation into a population containing only the first strategy. First we analyze the transition from Basic to Smart strategies. We consider the strategies B and a-B as the original strategies and study the possibility that they can be invaded by strategy S and a-S respectively. Second we analyze the transition from non-assessor to assessor strategies. We consider the strategies B and S as the original strategies and study the possibility that they can be invaded by strategy a-B and a-S respectively. In all cases, we recorded the average frequency of each strategy in the population over the last 10,000 rounds of each 100,000-round simulation and gave each strategy a score that was the mean of those values over the simulations in which it participated. All simulations were performed, unless otherwise explicitly provided, in the conditions that we call standard (Table 2).

To analyze the dynamic of the four strategies when they all compete together we started from a population composed of individuals of strategy B and a higher mutation rate of 0.003 towards any of the other strategies. Now we consider 500 replicas and 300,000 rounds.

In summary, we are interested in analyzing the hominin transition towards greater cognitive abilities to innovate and imitate. When developing our model we have assumed a series of conditions: a) the ability to imitate and innovate are underdeveloped, probably in a similar way to that of our first hominin ancestors; b) the abilities to imitate and innovate develop simultaneously in the cognitive transition from Basic to Smart; c) the cost associated with greater capacity to imitate and innovate is high enough

to stop such development in standard conditions; d) the cost of teaching is smaller than that of increasing the capacity to imitate and innovate; e) the cultural levels of the model can be understood, for example, as the number of refinements that accumulate in a process of stone tool making, so that a higher level is more difficult to innovate and to replicate accurately and more profitable in terms of fitness; f) when the parameters are analogous, we utilize similar values that were used in the pairwise contest in the Rendell et al. (2010) tournament.

3. Results

Fig. 1 shows the average cultural level reached by populations consisting of individuals of only one strategy, under standard conditions. The Smart strategy S increases the cultural level by 28% compared to the level of the Basic strategy B. Strategy a-B, even though its capacity for innovation and imitation of other individuals is lower, reaches a slightly higher level than the S strategy by using teaching. The strategy a-S increases its cultural level by 191% compared to the B strategy. By modifying the values of innovation k or imitation h , the cultural level of the S strategy is always greater than strategy B and the level of the a-S strategy is higher than a-B, where a-S always reaches the highest cultural level. Under the standard conditions of our model, the cultural level of the a-B strategy is greater than strategy S. However, strategy S can achieve a higher level than strategy a-B if the values of innovation k or imitation h are great enough. Fig. 1 also shows the mean lifetime payoff under standard conditions ($\alpha = 2$). The order of the 4 strategies from lowest to highest mean lifetime payoff is the same as for the average cultural level.

Fig. 2 show, for different values of α , the frequencies of the different strategies when competing in a pairwise contest. Fig. 2 shows the transition from Basic strategies (B or a-B) to the equivalent Smart strategies (S or a-S) respectively. The mean lifetime payoff of individuals S and a-S is greater than that of individ-

Fig. 1. Mean cultural level and mean lifetime payoff of the strategies B, S, a-B, and a-S, in standard conditions.

Fig. 2. Competition in pairwise contest for different α : The transition from Basic to Smart and from non-assessor to assessor.

uals B and a-B respectively and therefore is more likely to be selected as a parent. However, under the standard conditions of the model the cost of having one more round in the period of childhood prevents strategies S and a-S from defeating strategy B and a-B respectively. As the value of the payoff α increases, the strategies that acquire a higher cultural level became more competitive. In fact, the a-S strategy can beat the a-B strategy when α is sufficiently high ($\alpha = 4$).

Fig. 2 also shows the transition from a non-assessor to an assessor strategy. Assessor strategies a-B and a-S can displace strategies B and S respectively more and more easily as α increases. Only when $\alpha = 0.5$ does the cost of teaching offset the advantage of a higher cultural level, resulting in a tie.

These results are confirmed if the 4 strategies compete together, starting with a population only consisting of B strategy individuals. Figs. 3–5 summarize the results of the competition between the four strategies for different values of α .

When $\alpha = 0.5$ (Fig. 3), strategies a-B and B managed to stay in first place, but the a-B strategy takes a small advantage over B because it leverages better the largest average cultural level achieved in the presence of Smart strategies (S y a-S). None of the Smart strategies can compete with the Basic strategies (B and a-B) effectively. With $\alpha = 2$ (Fig. 4) the a-B strategy clearly displaced B, which loses the second place respect to a-S.

With $\alpha = 4$ (Fig. 5), the a-S strategy displaced a-B, and B was third. The S strategy was always last. Seen in relative terms and in all situations, the a-S strategy competes better against the S strategy than the a-B strategy against the B strategy.

4. Discussion

The success of cumulative culture depends on the ability to innovate and imitate. Thus, under equal conditions, the Smart strategies (S and a-S) achieve higher levels of cultural accumulation than Basic (B and a-B) strategies respectively, allowing the former to develop more complex behaviors and to increase their mean lifetime payoff (Fig. 1). Alternatively, the assessor strategies (a-B and a-S) obtain higher levels of cultural accumulation than non-teacher strategies (B and S) because of the increase in the efficiency of cultural transmission between parents and children. The average level of cultural accumulation of the strategy that best replicates the parental behavior (strategy a-S) fails to reach the 6th level. This is a consequence of the errors in the imitation (see for example Castro and Toro, 2014). We consider 10 cumulative cultural levels to show clearly the differences in the mean cultural level getting each strategy. However, qualitative results would be similar if we consider, for example, only 5 levels.

We assume that the cost of increasing the capacity to imitate and innovate is the most important limiting factor in our model. Thus, the cost of teaching is smaller than the cost of becoming Smart. We assume that, at equal imitative ability, it is easier for the father (who already knows the behavior) than for the child (that mimics) to detect mistakes in the imitation of a behavior. The cost that assessor strategies have to overcome (from B to a-B and from S to a-S) stems from time spent orienting children, during which they cannot exploit their behavior –i.e., one round for a-B and two rounds for a-S. Meanwhile, the cost of becoming a Smart strategy (from B to S and from a-B to a-S) is due to a longer childhood (from 5 to 6 rounds under standard conditions). Since the probability of death is the same for all, Smart individuals can, on average, be parents one round less than Basic individuals, which implies a remarkable handicap for the former. At this cost it is added that Smart individuals cannot successfully exploit the learned behavior during one more round in their childhood.

The results of the competition between the strategies depends on the costs and on the α parameter that increases the mean lifetime payoff that individuals obtain (Figs. 2–5). The results lead to two main conclusions. First, the transition of a non-teacher to a teacher strategy is more likely for individuals with higher capacity to imitate and innovate. That is, the transition from S to a-S is more likely than from B to a-B. This is because the cultural level reached is greater with a Smart strategy than with a Basic one and, therefore, the advantage provided by teaching also is greater. Second, the evolution from a Basic strategy to a Smart one is more likely if the strategies are assessor strategies. That is, the transition from a-B to a-S is more likely than from B to S. This is because the cognitive increase (more innovation and imitation) is better used in the presence of teaching than in its absence. These results are independent of the particular parameters we use in the model.

Fig. 3. Competition between the four strategies for $\alpha = 0.5$.

Fig. 4. Competition between the four strategies for $\alpha = 2$.

Fig. 5. Competition between the four strategies for $\alpha = 4$.

Furthermore, the results show that the transition from B strategy to a-B is more likely than from B to S. This is because we assume in the model that teaching is less costly than the increase in cognitive ability. Moreover, the parameters we use favor a higher cultural level for a-B than S. This last condition can be relaxed, allowing S to reach a higher cultural level than a-B. However, despite this, the lower cost of teaching favors the transition from B to a-B. In fact, Figs. 3–5 show how a-B may overcome not only S, but also a-S, that is clearly culturally superior.

In the model, the advantage of teaching comes from achieving high fidelity imitation between parents and children. The model shows that this increase could be enough for assessor teaching to evolve, even among individuals with low ability to imitate and innovate (strategy B). However, there is little evidence of teaching by evaluative feedback in primates (see Inoue-Nakamura and Matsuzawa, 1997; Tomasello and Call, 1997; Premack, 2004; 2007; Tennie et al., 2009; for a different opinion, see Boesch, 2003; 2012). Certainly, there are only two instances in the literature regarding active intention to teach among wild chimpanzees (Boesch, 2003) and their interpretation is not conclusive. We suggest that the implementation of teaching needed the emergence of individuals endowed with sufficient cognitive capacity to guide the learning of other individuals (Castro et al., 2018). Probably, chimpanzees do not surpass that cognitive threshold and cannot generate teaching by evaluative feedback.

The technological continuity over 50,000 years at the Acheulean site of Gesher Benot Ya'aqov (Sharon et al., 2011) implies that the capacity for social transmission of our ancestors was already high enough to generate and maintain a complex technological tradition. The difficulty of current humans to reproduce by imitation Oldowan tools (Morgan et al., 2015) suggests that maintenance of

the technological continuity at Gesher Benot Ya'aqov probably required teaching by evaluative feedback. Acheulean technology history offers evidence of both a long period of stability and a certain degree of refinements in the manufacture of bifaces for 1.5 million years (Shipton, 2010; Schick and Toth, 2017; Shipton, 2018). These improvements may be related to the expanding hominin brain, the extension of life history, the invention of knapping techniques, or some combination of the three (Shipton and Nielsen, 2018).

The results of our model are compatible with this data. On the one hand, errors in replication stop the accumulation at a certain level, showing fluctuations around it. On the other hand, an increase in cognitive abilities results in an increase in the cultural level achieved. In summary, the existing data support the idea that the development and maintenance of Acheulean technology required elementary forms of assessor teaching. As we have suggested before, once evolved primary forms of teaching the interaction among innovation, imitation and assessor teaching gave rise to an autocatalytic process of co-evolution that probably occurred in our species.

The 500,000 year old site of Boxgrove has produced the earliest reliable evidence for two key elements of Acheulean innovation: soft hammers (Pitts and Roberts, 1997), and platform preparation (Stout et al., 2014). The Boxgrove bifaces were manufactured by the large brained hominin *Homo heidelbergensis*. We think that technological changes in the daughter species *Homo neanderthalensis* and *Homo sapiens* can be considered a good example of a cognitive transition from Basic to Smart, or better from Smart to Smarter, in the context of assessor teaching or perhaps of a more advanced manifestation of teaching.

Finally we would like to suggest that some implications of our model are potentially archaeologically testable. Under conditions of

imitation with strong horizontal and weak vertical cultural transmission you might expect relatively wide variation in the morphology of stone tools around a single modal form, whereas with multiple assessor teaching lineages you might expect tighter variation around multiple modes representing distinct sub-types.

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