DOI: http://dx.doi.org/10.7551/978-0-262-32621-6-ch066

Gene-culture coevolution of language: measurement-interval dependence of evolutionary rate

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Understanding the origin and evolution of language is key to understanding humans. The relationship between the biological evolution of language ability and the cultural evolution of language itself is extremely complex and shrouded in controversy because these mechanisms interact with each other despite the difference in their time scales (Mesoudi et al., 2011). The concept of coevolution between language and brain, in which language adapts to the brain and the brain adapts to language, is considered important in integrating biological and cultural evolution of humans (Deacon, 1997).

On the other hand, cultural linguistic change is often assumed to be much faster than biological change. For example, Chater et al. (2009) showed, using a computational model, that genetic natural selection may not keep pace with rapid language change. However, it is known that the rate of evolution has a dependence on the interval of time over which the rates are measured (Gingerich, 1993). Rates of evolution can be measured in *darwins (d)*, which is a standardized unit of change in factors of e, the base of the natural logarithm, per millions of years (Gingerich, 1993).

$$d = (\ln(x_2) - \ln(x_1))/\Delta t \tag{1}$$

where x_1 is the mean trait value calculated at time t_1, x_2 is the mean value at time t_2, and Δt is the time interval between x_1 and x_2. Fig. 1 shows an example of the measurement interval dependence of the evolutionary rate of a quantitative trait. If the evolutionary process is directional (a-i), the rates are stable irrespective of measurement time interval (a-ii). However, if the evolution process is less directional or fluctuating (b-i), the rates are inversely correlated with the measurement time interval (b-ii). This is because the fluctuation strongly affects the measured rate when the interval is short, while the general trend affects the rate when the interval is long. Perreault (2012) found that, by analyzing archaeological data, the rates of cultural evolution are inversely correlated with the measurement interval. He claimed that this explains why cultural change appears to be faster than biological change (because we tend to measure cultural evolution on a short time scale) but concluded that cultural evolution is faster than biological evolution even when such a correlation is taken into account. This indicates the significance of this fine-grained comparison of evolutionary rates in the context of interactions between biological evolution of language ability and cultural evolution of language.

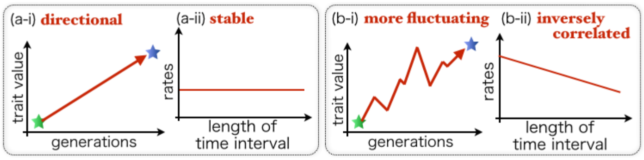

Figure 1: Examples of evolutionary trends for two quantitative traits and their associated evolutionary rates as a function of the measurement time interval.

The purpose of this study is to clarify the relationship between the rates of biological evolution of language ability and cultural evolution of language, focusing on their measurement-interval dependence. In order to analyze this, we employ a bottom-up computational framework for investigating possible scenarios for gene-culture coevolution of language, which has been proposed in our previous works (Azumagakito et al., 2013, 2014).

In this model, there are finite number of agents and languages in a one-dimensional space, and agents can communicate with each other using their shared languages (Fig. 2). Each language is represented as a point in the space, and its distance from the origin (El) represents its expressiveness, which contributes to the expected fitness benefit of a successful communication using that language. Each agent is also represented as a point and an area surrounding the point. This point represents the agent's innate language ability determined by its gene Ea, and the area represents agent's linguistic plasticity determined by its gene P. The agent can use any languages within its plasticity area for communication, incurring a cost proportional to the size of the area. In each generation, all possible pairs of agents make an attempt to communicate. If two agents share one or more languages, they can communicate successfully. This definition means that agents who can communicate with many other agents

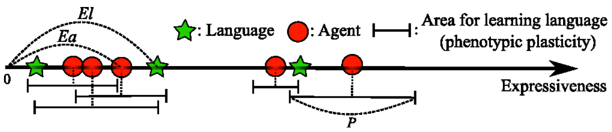

Figure 2: The linguistic space.

using expressive languages acquired with limited linguistic plasticity will have high fitness. After the communicative interactions of agents, biological evolution of language ability occurs according to a genetic algorithm.

Subsequently, the language population evolves according to four cultural processes: 1) Cultural change: the user of a language exerts a force that drags languages towards its location, 2) Division: a language is divided into two if the drag forces strongly pull it in opposing directions, 3) Extinction: any languages that are not used by any agents in one generation do not appear in the next generation, and 4) Fusion: when the distance between two languages is small enough, these languages are united into one language. Through the above processes, the agent population and the language population coevolve.

We conducted evolutionary experiments for 20,000 generations. The results showed that the agents and languages evolved to have high expressiveness through a cyclic coevolutionary process, which was discussed in our previous study (Azumagakito et al., 2014). Here, we measured evolutionary rates for languages (in terms of average El) and agents (in terms of average Ea).

Fig. 3 shows a typical coevolution process between (a) the average agent's trait and (b) language expressiveness, and their evolutionary rates measured over several time intervals. The x-axis ranges from 5000 to 20000 generations of evolution is not shown because there is no remarkable change of tendency. We see that both rates of evolution change dynamically and there are peaks for $\Delta t = 200$. These peaks correspond to rapid evolution of agents and languages. We also see that the rates of language evolution tended to be higher and fluctuate more than those of biological evolution in the case of $\Delta t = 200$. However, rates of language evolution became slower than biological rates when the time interval was long ($\Delta t \geq 1000$). In addition, Fig. 3 (c) shows linear approximations for both rates as a function of the time interval. The negative slopes clearly show their measurement-interval dependence. There was a statistically significant difference in the slopes ($p < 0.05$). Note that cultural rates were faster than biological rates when they were measured over a short time scale, but this reversed when the time interval was longer. This means that the measurement-interval dependence of the evolutionary rate of language is stronger than that of the rate of biological evolution. We propose that this is due to the lack of directionality in cultural evolution. This implies that biological evolution is more directional than cultural language evolution, and could therefore keep pace with language evolution.

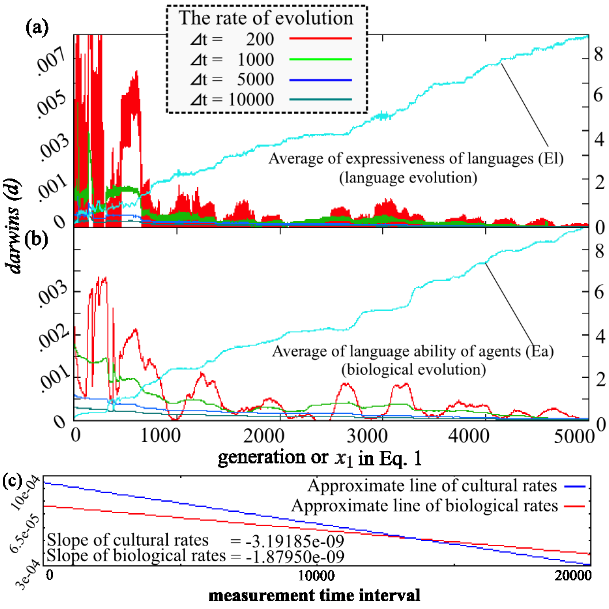

Figure 3: A typical coevolution process between (a) the average agent's trait and (b) language expressiveness, and their evolutionary rates measured over several time intervals. (c) Linear fits for both rates against the time interval over which the rates are measured.

Acknowledgements

This work was supported by Grant-in-Aid for JSPS Fellows (257917).

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