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# Iterated Teaching Can Optimize Language Functionality

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## Abstract

Experimental studies of the cultural evolution of language have focused on how constraints on learning and communication drive emergence of linguistic structure. Yet language is typically transmitted by experts who adjust the input in ways that facilitates learning by novices, e.g. through child-directed speech. Using iterated language learning of binary auditory sequences, we explored how language change is affected by experts' intention to teach the language to novices. Comparison between teaching chains and simple transmission chains revealed that teaching led to a greater rate of innovation which drove the emergence of more expressive languages consisting of shorter signals. This is the first study to show that during cultural transmission, teaching can modify, and potentially optimize, functional characteristics of language.

**Keywords:** Teaching; iterated language learning; cultural transmission; algorithmic complexity; compositional structure; combinatorial structure

## Introduction

Cultural transmission of knowledge proceeds via the social learning mechanisms of imitation, emulation and teaching (Boyd & Richerson, 1985; Richerson & Boyd, 2005). Of these, the adaptive value of teaching has recently received increased attention (Cavalli-Sforza & Feldman, 1981; Kline et al. 2013; Kline, 2015; Csibra & Gergely, 2009), highlighting in particular the ostensive use of language in the transmission of technological knowledge required for production of tools and other cultural artifacts (Caldwell & Millen, 2009; Morgan, Uomini, Rendell, Chouinard-Thuly et al., 2015). In its most general sense, teaching can be defined as any kind of behavior, intentional or not, that promotes learning by narrowing the range of inferences or behavioral options that another individual can pursue (Kline, 2015). Teaching is especially important for transmission of cognitively opaque cultural traits and traditions, i.e. those whose function is not immediately obvious, thereby contributing to cumulative culture (Mesoudi 2011). While transmission of simpler cultural traits may not benefit from additional teaching (Caldwell & Millen, 2009), once culture becomes more complex, teaching delivers additional benefits for the transmission process (Morgan et al., 2015).

In contrast, studies of the cultural transmission of language have mainly researched how constraints that

operate on observational learning drive the emergence of those structural features of language that support effective communication (Kirby, Cornish and Smith, 2008; Kirby, Tamariz, Cornish & Smith; 2015; Verhoef, Kirby & de Boer, 2014). These studies use the iterated language learning method whereby the result of learning in one generation of learners serves as input for the next generation. The picture that emerges from these studies is that cognitive capacity constraints in human learners promote compressibility of individual signals and entire languages, and that the requirements of efficient communication drive languages to be expressive. In tandem, these constraints – the need for transmission efficiency and for referential efficiency – lead to emergence of combinatorial linguistic structure, i.e. systematic associations of components of the signal with dimension of meaning (Kirby et al., 2015).

However, research on language development in children has presented substantial evidence that child language learners receive input that is specifically tailored to support learning, in the form of child-directed speech (e.g. Burnham, Kitamura, & Vollmer-Conna, 2002; Kempe & Brooks, 2005; Soderstrom, 2007). While there is considerable debate about whether child-directed speech is universal (e.g. Broesch & Bryant, 2013; Falk, 2004; Schieffelin, 1985) and constitutes intentional teaching or not (e.g. Singh, Morgan & Best, 2002; Uther, Knoll & Burnham, 2007), functionally it qualifies as a behavior that not only provides local enhancement by directing the learner's attention to relevant information (Kline, 2015) but also pre-samples the input in a way that directs learner inferences towards correct hypotheses about language (Eaves, Feldman, Griffiths & Shafto, 2016). For learning to occur, no ostensive cues or direct feedback are required as long as the statistical properties of the modified input ensure improved learning. In this study, we explore how tailoring the input in such a way for the learner shapes the process of language transmission.

If teaching leads to modification of the input to promote correct inferences about language then we can make predictions about the directions in which iterated teaching will change the structure of the emerging system, compared to simple transmission that is only constrained by the learner. Previous iterated language learning studies have highlighted a number of structural features that emerge

because languages need to be learnable and communicatively efficient. We predict that emergence of these features should be facilitated under conditions of teaching: First, if teaching accommodates learnability constraints one would expect transmission fidelity to increase even faster in chains where teaching takes place, compared to simple transmission. Second, as languages evolve to be efficient signaling systems signals acquire combinatorial structure by which smaller meaningless subcomponents are recombined to improve signal discriminability, a feature which supports transmission across noisy channels (Verhoef, 2012; Verhoef et al., 2014; Roberts, Lewandowski & Galantucci, 2015) and should be enhanced through teaching. Third, in order to be communicatively efficient, languages also need to maintain expressivity by avoiding under-specification and ambiguity, another feature we expect to emerge faster under conditions of teaching. Fourth, languages become more systematic and self-similar, a property that, akin to phonotactic rules, supports learnability by reducing combinatorial freedom. This feature should also be enhanced by teaching. Finally, emerging compositional structure serves to systematically link meaningless components of the signals to underlying dimensions of the meaning. However, combinatorial structure requires communicative pressure in addition to language transmission (Kirby et al., 2015; Nowak & Baggio, 2016). However, in order to isolate the effect of teaching, and in the interest of feasibility we started our exploration of the role of teaching in iterated language learning with a simple transmission study that did not impose communicative pressure on learners. It is, however, conceivable that teachers may still modify the input to enhance combinatorial structure to highlight this functional aspect of language.

## Method

The present experiment compares transmission of an ‘alien’ language when learners’ output generated during testing is faithfully represented as input to learners in the next generation (Simple Transmission condition) with transmission of the language through chains of learners who are asked to teach the language to the next generation after training (Teaching condition). Teaching in this set-up constitutes demonstration of the language to the next learner without any verbal explanation or instruction. The crucial question is if teachers modify the input when presenting the language to the next learner in a way that goes beyond modifications that are due to constraints on reproduction.

**Participants:** Sixty undergraduates were recruited at the University library for participation in a transmission chain study. Participants were assigned numbers corresponding to their slot in one of six chains, and were called into the test area when the previous participant had finished the training phase. Performance of these participants was compared to that of sixty other participants who had been tested in a different simple transmission study conducted earlier

(Kempe, Gauvrit, Gibson & Jamieson, submitted). The ‘alien’ language used in this experiment consisted of high and low tones assembled into 6 or 8-tone sequences. This signaling system was developed to eliminate any familiarity with the signals that could bias learners towards preferences for specific aspects of combinatorial structure.

**Materials:** Two 500 ms sine-wave tones (high: 440 Hz = musical note *a*; low: 293.7 Hz = musical note *d*) were synthesized and recorded onto a purple and a green answer buzzer of 9 cm diameter each. The fixed tone duration made it impossible to modify the length of the tones if pressing the buzzers for longer periods of time thus eliminating duration as a property of the signals. Seed languages consisted of random sequences of high vs. low tones, which were either six or eight tones long. These binary sequences instantiating the ‘words’ in the ‘alien language’ were paired with eight colored objects differing in shape (spiky ‘kiki’-type vs. fluffy ‘bouba’-type), size (2 x 2 cm vs. 4 x 4 cm) and brightness (25% vs 75% saturation) (see Figure 1), which were printed on laminated cards sized 5 x 8 cm. All objects also had unique properties due to differences in specific shapes and hues.



Figure 1: Meanings associated with the signals in the ‘alien buzzer language’.

**Procedure:** After signing a consent form, participants in both conditions were told they would learn an ‘alien’ language used by a species of aliens that had no mouth and therefore used buzzers for communication. Participants were then shown six of the eight cards one at a time to familiarize them with the ‘alien’ objects. Training proceeded in an incremental fashion: In the Simple Transmission condition, participants were given a demonstration of the binary buzzer sequence for each card, and asked to repeat it. Demonstration and practice were then immediately repeated resulting in two consecutive training trials per card in total, before proceeding to the next card. Order of cards was randomized for each participant by shuffling the cards. After training, participants were shown the cards one at a time, and asked to produce the ‘alien buzzer words’ to the best of their abilities. Their responses were videotaped and coded to allow them to be presented to the next participant. To prevent the languages from degenerating, a ‘homonymy filter’ (Kirby et al., 2008) was applied by which up to two duplicates were withheld and only six items were presented during training. In case of no duplicates, two cards were withheld at random; in case of one duplicate, the second card was withheld at random. This manipulation was used to encourage productivity and to prevent languages from accumulating homonyms.

In the Teaching condition, chains were also seeded with six out of eight cards, to maintain compatibility with the

Simple Transmission condition. In Generation 1, training proceeded in exactly the same way as in the simple transmission condition. However, from Generation 1 onwards, after training, participants were asked to ‘teach’ the language to the next participant in the chain who was called into the testing area at that time. When teaching, participants were instructed not to provide verbal comments or instructions but to simply demonstrate the buzzer sequences twice to the next participant, allowing them to repeat the sequence after each demonstration.

## Results

Participant buzzer responses were videotaped and coded for further analyses. Inter-coder reliability, determined for 17% of trials, was 94%. All dependent variables were analyzed using Growth Curve Analyses (GCA) with centered fixed effects of Condition (Simple Transmission vs. Teaching) and Generation, and random intercepts of Chains as well as random slopes of Generation (Winter & Wieling, 2016).

**Expressivity:** When participants were asked to teach, languages remained more expressive than in the simple transmission condition, which was more prone to degenerate into underspecified languages containing more homonyms (Figure 2). This was indicated by an effect of Condition,  $\beta = 0.36$ ,  $t = 3.09$ ,  $p < .05$ , on the number of unique sequences. No other effects were significant.

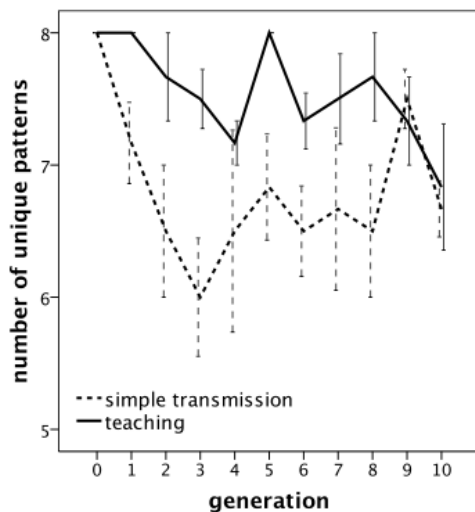


Figure 2: Number of unique sequences (out of 8) in the Simple Transmission and the Teaching chains.

**Transmission Accuracy:** Transmission accuracy was measured using the length-normalized Levenshtein edit distance (LED). LED decreased overall, as evidenced by an effect of Generation,  $\beta = -0.01$ ,  $t = -4.01$ ,  $p < .01$ . A main effect of Condition,  $\beta = 0.03$ ,  $t = 2.63$ ,  $p < .05$ , and the marginal interaction of Condition with Generation,  $\beta = 0.01$ ,  $t = 2.0$ ,  $p = .07$ , suggest that transmission accuracy decreased faster in the Simple Transmission condition (Figure 3). In other words, when participants were asked to

teach they introduced more innovations than when they simply tried to reproduce the binary sequences.

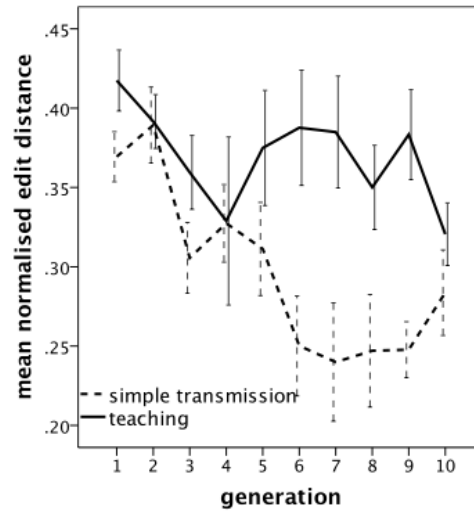


Figure 3: Mean length-normalized Levenshtein edit distance, an inverse measure of transmission accuracy, in the Simple Transmission and the Teaching chains.

**Self-similarity:** Self-similarity was quantified as the average pairwise length-normalized LED of all pairs of sequences in a language, to provide a measure of how similar to each other all different sequences within a language were. The CGA yielded no significant effects suggesting that this kind of systematicity within a language did not reliably emerge in either of the conditions (Figure 4).

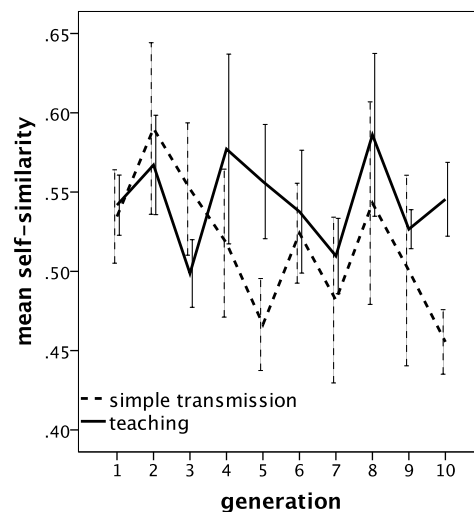


Figure 4: Mean self-similarity in the Simple Transmission and the Teaching chains.

**Length:** Sequences had started out with an average length of 7 tones in Generation 0. In the Teaching condition, sequences remained of roughly the same length, which was significantly shorter than in the Simple Transmission condition,  $\beta = -0.78$ ,  $t = -2.39$ ,  $p < .05$ . The interaction

between Condition and Generation,  $\beta = -0.20$ ,  $t = -2.86$ ,  $p < .05$ , suggested that sequences increased in length only in the Simple Transmission condition (Figure 4).

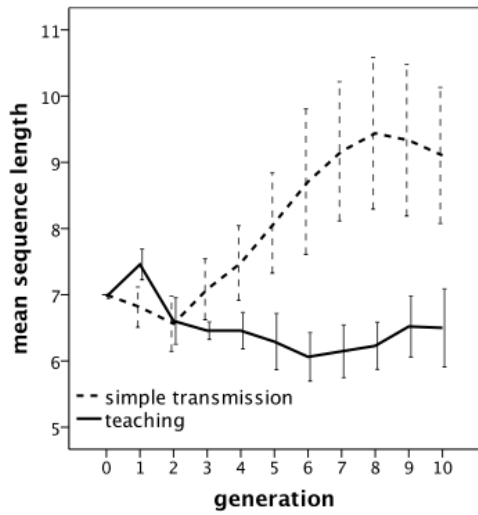


Figure 5: Mean sequence length in the Simple Transmission and the Teaching chains.

**Combinatorial structure:** Structure of individual signals was operationalized as algorithmic complexity, using an estimate developed for short binary strings based on the coding theorem method (Gauvrit, Soler-Toscano, Zenil & Delahaye, 2014; Zenil, Soler-Toscano, Delahaye & Gauvrit, 2015). This measure provides an inverse estimate for the amount of structure of each sequence relative to the variation in structure possible for all sequences of any given length (Figure 5). GCA did not yield any significant effects although the effect of Generation,  $\beta = -0.04$ ,  $t = -2.02$ ,  $p = .07$ , fell short of significance. Thus, there was no evidence that teaching lead to more structured sequences; in fact, the trend pointed in the opposite direction.

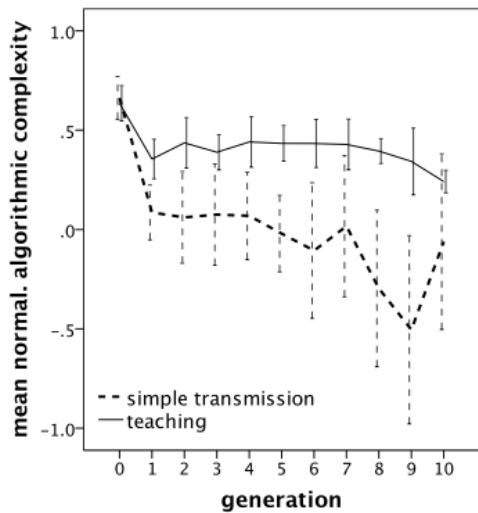


Figure 6: Mean length-normalized algorithmic complexity in the Simple Transmission and the Teaching chains.

**Compositional Structure:** To establish whether compositional structure emerged, we calculated the Pearson product-moment correlations between differences in the three meaning dimensions of all pairings of meanings and associated differences between pairings of associated signals within each language, using 10,000 iterations of a Monte Carlo process to obtain a standardized score. This measure remained below the value associated with  $p = .05$ , and did not differ between conditions and generations indicating that no compositional structure had emerged (Figure 7).

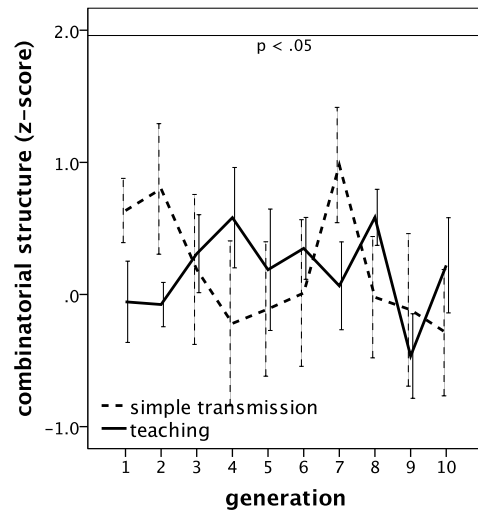


Figure 7: Mean combinatorial structure in the simple transmission and the teaching chains. The horizontal line indicates  $z = 1.96$ ,  $p = .05$ .

## Discussion

We compared six teaching chains with six simple transmission chains to explore the effect of teaching during cultural transmission of language. As this was an exploratory study, we did not include a requirement to engage in referential communication. Thus, it was not unexpected that combinatorial structure did not emerge (Kirby et al., 2015), and we found no evidence that teachers would introduce it spontaneously.

What we found was that although transmission accuracy increased overall, it was significantly lower in the Teaching condition, counter to our expectations. Thus, considerably more innovations were introduced into the signals when participants were asked to teach rather than just to reproduce what they had learned. We suggest that these innovations served to stabilize certain features of the languages that the teachers considered crucial. The most notable change from Simple Transmission performance achieved through innovation in the Teaching condition was to maintain expressivity of the language: The number of different sequences within the taught languages remained high thus preventing these languages from degenerating by accumulating homonyms. This is an interesting result

because previous research had demonstrated that without a strong incentive to communicate, capacity constraints of the learners drive languages towards under-specification and ambiguity (Kirby et al., 2015). What our findings suggest is that teaching can override this tendency, presumably due to strong biases about the functional destination of language, which is to be expressive, i.e. referentially efficient. It is noteworthy that the expressivity advantage in the Teaching condition arose even though we applied a homonymy-filter in the Simple Transmission condition to prevent the languages from degenerating. Without this filter, languages in the Simple Transmission condition would have accumulated even more homonyms (Kirby et al., 2008), presumably further increasing the difference to the Teaching condition.

Another feature that remained stable in the Teaching condition was sequence length: Teachers managed to maintain sequence length at around the original 7 tones while in the Simple Transmission condition, sequence length increased dramatically. Stabilizing or even reducing length is a strategy that can ensure learnability and transmission accuracy by keeping the form of signals within the limits imposed by working memory constraints. As this brevity constraint operated only in the Teaching condition it may reflect a cooperative adjustment on the part of the teacher designed to aid the learner.

The drive to maintain distinct signals in the Teaching condition also seemed to prevent the emergence of self-similarity of languages, a measure of systematicity that is akin to phonotactic rules. This is not surprising if teachers attempted to resolve the trade-off between expressivity of the language and brevity of the signals, as utilizing the full space of distinct binary sequences of shorter lengths restricts opportunity to achieve self-similarity. In the Simple Teaching condition, there was more of a trend towards systematicity although it did not reach statistical significance.

We had also hypothesized that teaching would lead to a faster increase in combinatorial structure to improve transmission efficiency. For the binary sequences used as signals in this study, introducing combinatorial structure would entail establishing subcomponents (e.g. *ab* or *aab*) that can be recombined using operations like repetition or mirroring, as in strings like *ababab* (-0.75 [numbers in parentheses are the associated values of length-normalized algorithmic complexity] or *aabaabaab* (-1.43). In contrast, complex strings like *bbaaab* (1.43) or *bbaaaabba* (2.02) do not contain combinations of discernible subcomponents. According to our hypothesis, the Teaching condition should have given rise to more sequences of the former than the latter type. However, our data showed exactly the opposite trend: Although not significantly so, length-normalized algorithmic complexity tended to be higher in the Teaching condition, indicating less combinatorial structure than in the Simple Transmission condition. One possible explanation for this finding is that when trying to produce as many different sequences as possible while maintaining brevity of

the signals, teachers inevitably sample more densely from the distribution of shorter sequences thereby inevitably utilizing more sequences of higher complexity. On the other hand, when the brevity constraint is relaxed, learners in the Simple Transmission condition may produce longer sequences yet processing capacity limitations will force them to settle for more structured ones, which are made up of a limited repertoire of subcomponents.

This pattern of results shows that when teaching, which in this study entailed knowingly serving as input-generating models, participants changed their behavior to adjust the input so as to constrain learner hypotheses in accordance with their own tacit knowledge about how languages function. Specifically, they were negotiating a trade-off between referential efficiency and transmission efficiency by introducing innovations that allowed them to generate unique sequences for each meaning, to prevent languages from degenerating into under-specified systems, while at the same time facilitating transmission fidelity by stabilizing the length of these sequences. It can be argued that the biases that shaped this teaching behavior reflect participants' knowledge about the functionality of language as it was acquired through their native language use and, thus, these biases may not be informative about the role teaching may have played in language evolution. However, learners in the simple transmission condition had access to exactly the same knowledge yet without the motivation to teach those biases were overridden by the drive towards compressibility. Thus, whatever the origins of the knowledge about the functionality of language are, our findings suggest that this knowledge affects teaching.

To summarize, the results of this study support the idea that teachers modify the input to learners in ways that reflect their biases about the functional utility of a cultural trait. Applying this idea to the study of the cultural evolution of language means that theories of language transmission need to include teaching into the suite of transmission mechanisms under consideration. We hope that our findings will inspire more detailed explorations of the role of teaching in the cultural evolution of language in the future.

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