Simplicity and Informativeness in the Evolution of Combinatorial Structure

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Abstract

Cultural symbol systems, such as language, music, or pictorial diagrams, are crucial for the storage and transmission of knowledge, and ultimately underpin our capacity for culture. One important feature of these systems is their combinatorial structure: the reuse of building blocks to compose new concepts or ideas. Here, we conduct a study that combines iterated learning with a communication game to show that combinatorial structure is not inevitable, but rather arises as a trade-off between the simplicity of signals and the amount of information they convey. Our results provide additional insights into the role of communication in the emergence of signal structure, as a force that maintains complexity and creates alignment. These results validate a key theoretical prediction about how combinatorial structure arises in the interplay of learning and use, and shed light on how signaling systems such as language have become such powerful and flexible tools in human cognition.

Keywords: language evolution; discreteness; systematicity; color categories; communication game

Introduction

Communication systems such as language are crucial for the storage and transmission of human knowledge, ultimately underpinning our capacity for cumulative culture. From phonemes in spoken words to strokes in written characters or gestural features in sign language, a key characteristic of these systems is their use of a small set of building blocks to create an infinite number of symbols, a property known as *combinatorial structure*. However, emerging sign languages (Sandler, Meir, Padden, & Aronoff, 2005; Sandler, Aronoff, Meir, & Padden, 2011) and signaling systems such as air marshalling or diving signals don't seem to rely on recombinations of smaller meaningless building blocks. This suggests that combinatorial structure is not universal, and raises the question of how it could have evolved in human culture.

Recent work in evolutionary linguistics points to the interplay of individual cognitive biases and functional constraints that play out over the course of cultural transmission as one possible explanatory route (Kirby & Hurford, 2002; Kirby, Tamariz, Cornish, & Smith, 2015; Tamariz & Kirby, 2016; Christiansen & Chater, 2016; Smith, 2021). According to this view, combinatoriality is an efficient solution to the problems that arise when languages are culturally acquired, used, and transmitted. On this view, communication systems evolve to strike a balance between the simplicity of their signals and the amount of information they convey.

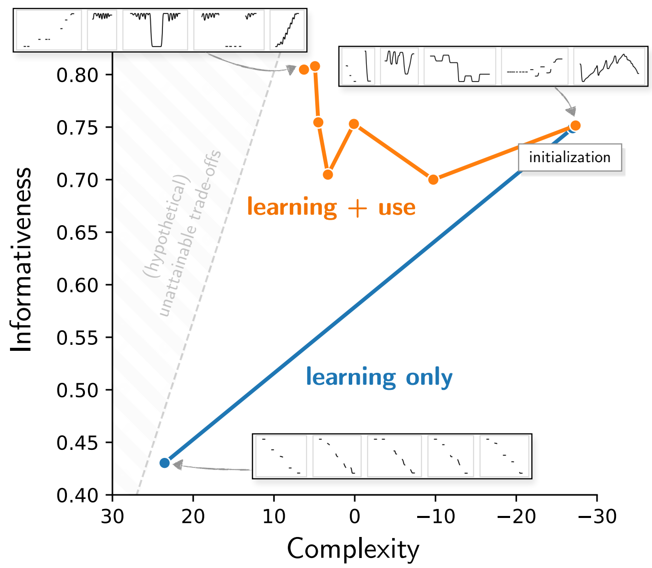

Figure 1: Signaling systems show different evolutionary trajectories with/without communicative biases. Our results support the *trade-off hypothesis*, according to which combinatoriality develops by balancing complexity and informativeness in language learning and use.

The trade-off hypothesis

The idea that linguistic structure emerges as a result of opposing pressures has a long history in linguistics (Zipf, 1949; Martinet, 1952; Hockett, 1960). More recent work has grounded this idea in mathematical frameworks based on information theory (e.g., Plotkin and Nowak (2000); and see Gibson et al. (2019) for a review of recent work). According to the cultural evolutionary account of language structure, communication systems evolve under distinct pressures related to learning and use (Kirby, Griffiths, & Smith, 2014; Kirby et al., 2015; Tamariz, 2017; Smith, 2021).

Pressures for *simplicity* are thought to arise from inductive biases in learning, where learners prefer simpler languages over complex ones (Hsu & Chater, 2010; Hsu, Chater, & Vitányi, 2011), exemplifying a more general inductive principle in human cognition (Vitanyi & Ming Li, 2000; Chater & Vitányi, 2003). These preferences are then amplified in cultural evolution by iterated learning, where systems are passed down through generations of learners (Smith, Kirby, & Brighton, 2003). This suggests that language evolution operates like a cultural ratchet, where preferences about language structure accumulate over time but are rarely lost.

However, an inductive bias for simplicity alone can lead to signal collapse, where signals become too similar to be communicatively useful as they simplify. (Kirby et al., 2015; Motamedi, Schouwstra, Smith, & Kirby, 2019). To prevent this,Spike, Stadler, Kirby, and Smith (2017) have argued that a systemic bias against ambiguity is necessary, typically instantiated in the form of referential communication. Communicative interaction creates a pressure for *informativeness* that selects for systems that allow users to make distinctions and communicate efficiently, which in turn limits language simplification (Kirby et al., 2015).

Previous research has shown that features such as compositionality (Kirby et al., 2015), human-like semantic category systems (Carr, Smith, Cornish, & Kirby, 2017; Kemp, Xu, & Regier, 2018), and systematicity (Motamedi et al., 2019) can result from balancing learnability and informativeness. However, it is unclear how these pressures might be aligned with learning and use (Gyevnar, Dagan, Haley, Guo, & Mollica, 2022). Some have suggested that a bias for informativeness might be built into the learning process itself (Fedzechkina, Jaeger, & Newport, 2012; Carstensen, Xu, Smith, & Regier, 2015), a view that has been challenged by Carr, Smith, Culbertson, and Kirby (2020). On the other hand, communicative interaction may create additional pressures for simplicity, as speakers prefer to say as little as possible to reduce effort. This has been a central idea in theoretical models such as Kemp and Regier (2012); Kemp et al. (2018); Zaslavsky, Kemp, Tishby, and Regier (2019), and raises the question of whether both simplicity and informativeness can arise from the communicative task alone.

Research questions and hypotheses

How do these considerations apply to combinatoriality? Previous experiments (Verhoef, Kirby, & de Boer, 2014; Hofer & Levy, 2019) have suggested that combinatorial structure may indeed emerge through cultural evolution. However, rather than a communicative task, these studies have used an artificial informativeness criterion to prevent signal collapse. The inclusion of such a task is important because communication is not a passive filter, but a process of actively modifying signals to meet communicative needs.

Experiments that included communication have focused on compositionality (Kirby et al., 2015) and systematicity in gesture (Motamedi et al., 2019), but these findings may not translate to combinatoriality, which does not necessarily involve structured, compositional meaning spaces. Finally, building on their earlier work on compositionality (Kirby et al., 2015), Kirby and Tamariz (2022) have explored the role of simplicity and informativeness in the emergence of combinatoriality using computer simulations. Their results are consistent with the trade-off hypothesis but only theoretical in nature. This motivates us to investigate experimentally how combinatorial structure can arise from simplicity and informativeness, in the presence of a real communicative task, and to test how these pressures map onto learning and use.

The predictions of the trade-off hypothesis are illustrated in Figure 1 with a simple example: Languages subject to learning pressures only may lose communicative utility due to excessive simplicity. In the presence of communication, signaling systems balance simplicity and informativeness by introducing combinatorial building blocks. This setup also allows us to study the role of communication in imposing additional simplicity constraints, as well as selecting for informativeness. In summary, we are testing two hypotheses.

- **Trade-off hypothesis.** Combinatorial structure emerges as an efficient solution to competing pressures for simplicity and informativeness.
- **The role of communicative efficiency.** Speaker-related processing considerations in the communication constitute an additional source of simplicity pressures.

Methods

Experimental design

To test these hypotheses, we developed an online multiplayer experiment that allows us to independently vary subjects' exposure to a learning phase and a communication phase.[1] Two experimental conditions are compared (Figure 2C). In a *learning-only condition* subjects learn miniature signaling systems comprised of five signal/referent pairings through repeated exposure (Figure 2B) and then reproduce them. Languages are subsequently transmitted to a new set of subjects as part of an iterated learning setup. The *combined condition* adds a communication game after learning. After concluding the learning phase, participants who were exposed to the same input language are paired up and play a simple reference game. This allows us to determine the effect of communication on the emergence of combinatorial structure by comparing output after learning and after communicative use.

Participants 736 native English-speaking participants from the US or Canada with no hearing impairments were recruited for the main experiment via Prolific. 251 additional participants were recruited for a rating study, and 138 for a follow-up measurement (see below). Participants wore headphones, verified with a screening tool (Woods, Siegel, Traer, & McDermott, 2017). Data was collected on separate days and input languages and communication partners were assigned randomly. 181 participants completed the learning-only condition, 555 the combined condition, over 6 generations.

Stimuli and signal modality Following Hofer and Levy (2019), we use a virtual adaptation of a slide whistle instrument, a signal space, first introduced by Verhoef (2012), which produces continuous auditory signals with a distinct

[1] See http://www.tinyurl.com/vuma for a demo of the experiment.

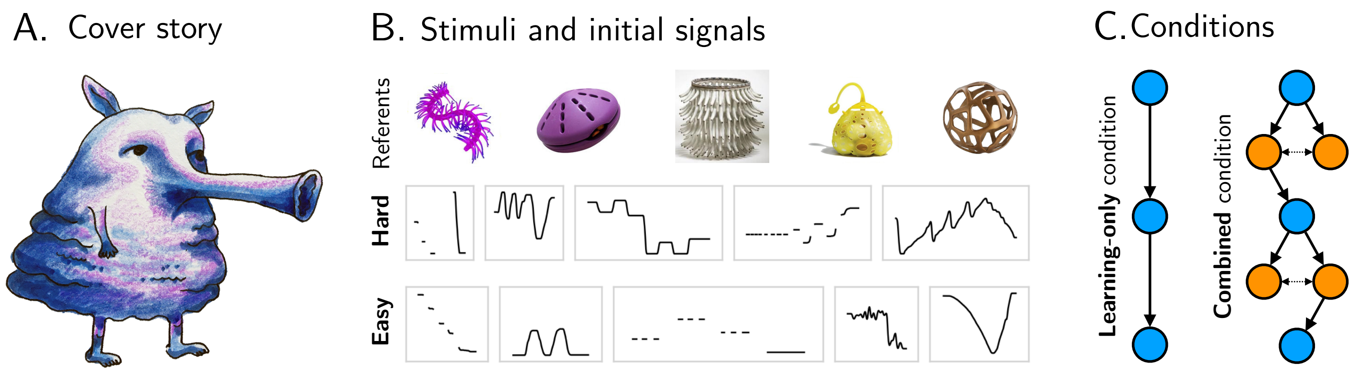

Figure 2: **A**. In the cover story, subjects were told that they learn signals produced by aliens on planet Vuma, who communicate using their whistle-like trunk. **B**. Data for two separate initial conditions was collected, where either five individually simpler or five slightly more complex signals were paired with novel visual referents taken from (Lewis & Frank, 2016). The assignment of referents to signals was randomized across chains and between successive generations. **C**. The two different experimental conditions.

pitch and audible/inaudible dimension. Figure 2B shows example signals, here plotted as pitch traces over time, showing the audible parts of the whistled signals. Participants were given a cover story according to which they are helping scientists study an alien language on planet Vuma by learning signals in the Vumanese language (see Figure 2A and Figure 3 for a depiction of the on-screen 'whistle' interface).

Two initialization languages were used for the transmission chains, taken from 40 whistled signals with complexity ratings from a pilot study (Figure 2B). One language was easy, the other hard to address potential ceiling effects in communication performance seen with the easy initialization. Referents for the signals were taken from a set of novel objects (Lewis & Frank, 2016) and randomly assigned to each chain. To prevent iconic mappings, signal-referent mappings were randomly permuted across chains.

Procedure

Learning phase The goal of the participants in the first phase was to learn the whistled signals and their corresponding referent as well as they could. Training consisted of five blocks in which subjects listened to and imitated signals using the on-screen whistle instrument. This was followed by a 2-AFC task where subjects heard each of the five signals in random order and were asked to choose between two referents, including the correct one and a distractor, to assess how well subjects learned the signal-referent pairs. Subjects were given a fixed payment and an additional performance-related bonus, depending on how well they remembered the signal-reference mappings in the 2-AFC task.

Communication phase Subjects assigned to the combined condition participated in a communication game after learning. We collected data from 362 participants, excluding subjects who completed the learning phase but were not matched with a partner after waiting for 15 minutes, or who could not complete the game because their partner disconnected. This represents approximately 15 games per generation and transmission chain, across 6 generations of 11 and 12 transmission chains, respectively. A game consisted of a pair of subjects exposed to the same input language during learning (i.e., subjects belonging to the same transmission chain). After receiving brief additional instructions, subjects began the experiment as either the speaker or the listener, chosen at random. These roles changed every 5 trials after each of the referents had appeared once as a target (see Figure 3), for a total of 50 trials. In each trial, a target referent is randomly selected from the remaining referents and shown to the speaker. At the beginning of their first speaker phase, subjects were able to replay and review the signals they produced in the learning phase to facilitate recall. The speaker then records a whistle signal that is transmitted to the listener in real time. After the listener makes their choice, both speaker and listener see which referent was selected and, if applicable, the target referent. Players are jointly rewarded for a correct guess. If incorrect, the listener gets to additionally replay the signal their partner last used for the referent they incorrectly selected.

Transmission In the combined condition, the language transmitted to the next generation is randomly selected from the languages produced by the two players in their last speaking phase. This is done because previous research has found that mixing languages for transmission can greatly attenuate transmission biases–at best, delaying the emergence of regularities, and at worst, introducing additional transmission biases that are still poorly understood (Navarro, Perfors, Kary, Brown, & Donkin, 2018; Smith et al., 2017; Saldana, Kirby, Truswell, & Smith, 2019). Languages in the learning-only condition are transmitted directly because they involved only a single learner.

Measuring simplicity and informativeness

Complexity ratings To evaluate simplicity/informativeness trade-offs, we need to measure language complexity. In-

Figure 3: Snapshots of the learning and communication phases, showing the virtual slide whistle that participants controlled using their mouse/trackpad and the space bar.

stead of using information-theoretic measures (such as, e.g., in Verhoef et al., 2014), which rely on specific assumptions about the nature of building blocks and segment boundaries, we used a rating study. 251 participants rated 95 randomly selected languages on a one-dimensional slider, which were presented to them visually (see Figure 4), judging how regular they appeared. The scores were averaged and normalized to give a language complexity score. Collecting data for languages before and after learning and communication allowed us to assess not only how languages develop overall, but also in response to each experimental phase.

Figure 4: An example of a language presented to subjects in the complexity rating study.

Measuring informativeness Informativeness is defined in terms of how well a language learned in the experiment facilitates performance on the communication task, measured in terms of average communication accuracy. To compare the combined condition with the learning-only condition, in which no communication took place, a separate experiment was conducted using the final languages from both conditions after 6 generations of transmission. 138 new subjects were recruited for this experiment. We predicted that subjects would perform worse communicating with languages from the learning-only condition, as these languages are thought to be primarily optimized for simplicity at the expense of expressiveness.

Results

We begin with a baseline analysis of the learning and communication before discussing the results in light of the two hypotheses presented earlier.

Learning phase

Following previous work by Verhoef et al. (2014), we define the learnability of a language in terms of the average similarity between signals before and after the learning task. Signals are compared using Dynamic Time Warping (DTW; Sakoe & Chiba, 1978), which computes time-shifted alignments. We found a main effect of generation on learnability ($t = -2.55, p < 1e{-3}$), indicating that languages became more learnable over time, but no significant interactions between generation and condition or initialization. A paired t-test comparing average learnability across initializations indicates that languages in the easy initialization seem to be more learnable overall compared to the hard initialization ($t = 4.2, p < 1e{-4}$).

In terms of their recall of signal-referent mappings in the 2-AFC task, subjects average 96% accuracy (4.8/5) in the combined condition, which is significantly higher than the learning-only condition accuracy of 87% (4.35/5) as indicated by a paired t-test ($t = -3.9, p < 1e{-3}$), a result which is expected assuming that communication pressures help maintain signal discriminability.

Communication phase

Defined as the average number of correct guesses in a game block, Figure 5 shows that communication accuracy is significantly above chance across all generations for both the easy and hard initializations ($p < 0.01$ on one-sample t-tests for all but one case when testing average performance against upper bound chance performance). Chance performance is indicated by the blue region, where the lower bound assumes sampling with replacement, and the upper bound represents sampling without replacement under the assumption that past samples are perfectly remembered. There was a significant main effect of game block on performance ($t = 3.5, p < 1e{-4}$), suggesting that players increasingly coordinated their behavior over the course of a game.

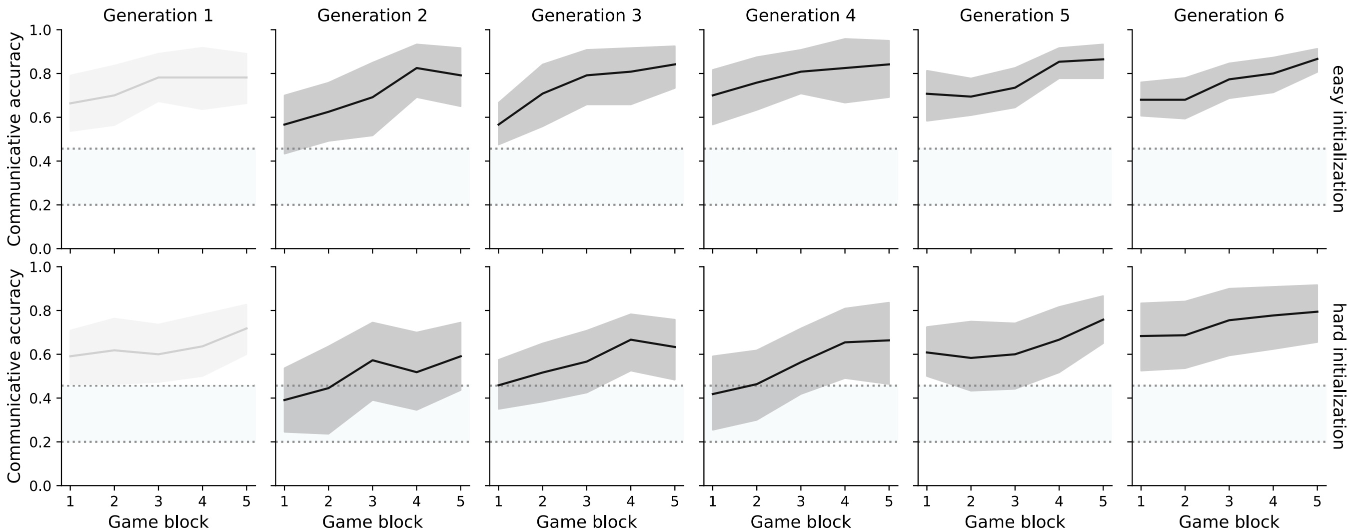

Figure 5: Results from the communication game, showing communication performance across blocks. Data are averaged across 11 participants/transmission chains each in the easy and hard initialization; error bars correspond to 95% bootstrapped confidence intervals. Performance increases over the course of communication games, suggesting alignment and conventionalization. Additionally, performance increases across generations in the harder initialization in the bottom row. While statistical analyses below are performed on all generations, the initial generation is displayed with more transparency to delineate possible effects of experimenter-curated initializations from generations in which subjects learned from the output of other subjects.

Comparing the effect of initialization on communication performance in the first generation using a paired t-test, results indicate better performance with the easy initialization compared to the hard initialization ($t = 2.52, p = 0.013$). Our regression model showed a significant interaction between generation and initialization ($t = 3.012, p = 0.003$), though while performance did not increase across generations in the easy initialization ($t = 1.57, p = 0.116$), it did so in the hard initialization ($t = 3.27, p = 0.001$), suggesting that players benefited from a cultural ratchet that gradually optimized languages for communication.

The trade-off hypothesis

We now consider the hypothesis that combinatorial structure arises from a trade-off between simplicity and informativeness. First, the result for our complexity measure, shown in Figure 6A, indicate that the complexity of languages decreased over time in both conditions, but the decrease was faster and more pronounced in the learning-only condition, as supported by a significant difference in the regression slopes of transmission chains between the two conditions ($t = 3.28, p = 0.004$). We hypothesize that this difference arises due to the communication task's pressure for informativeness, which counteracts and limits the complexity loss resulting from the learning task.

To visualize complexity in relation to informativeness, Figure 1 shows complexity scores against communicative utility scores obtained from the communication task. The orange line shows languages in the combined condition. One further data point for the combined condition and data for the learning-only condition was obtained by running an additional learning and communication experiment, as described in the methods section. The figure shows that in the combined condition, languages maintain a balance between simplicity and communicative utility, which is achieved through the introduction of combinatorial patterns. Meanwhile, in the learning-only condition, languages continue to lose complexity to the point of oversimplification. These results support the hypothesis that combinatorial structure arises as a solution to balancing the opposing demands of simplicity and informativeness in language.

The role of communicative efficiency

Our analysis of the second hypothesis focuses on the impact of communication on language complexity. Contrasting languages' relative complexity before and after the communication phase, results from Figure 6B indicate that language simplification only occurs as a result of learning and not communication. On the contrary, we observe that communication actually slightly increases language complexity ($t = -5.77, p < 1e-07$), as indicated by a paired t-test on averaged relative complexity values. This outcome is unexpected as we anticipated that the sender-related pressures during communication would simplify signals.

One possible explanation is that communication simplifies individual signals but not languages as a whole. During communication, speakers may simplify their effort in producing each signal individually, while during the learning phase they simplify at the language level, which may explain why communication temporarily increases language complexity.

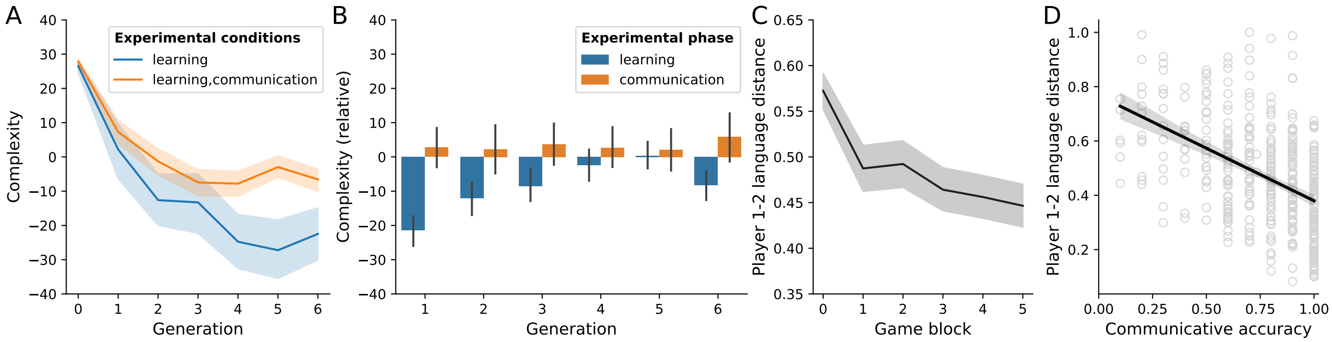

Figure 6: **A.** Results from the structure rating experiment. Languages in the learning only condition become more simple over time. **B.** Comparing complexity ratings of systems before and after the learning and communication tasks, it is shown that complexity only decreases over the course of the learning phase while communication even marginally increases complexity. **C.** During the communication game, signal repertoires of the two players align and become more similar to each other. **D.** This alignment predicts communication performance as players who are more aligned achieve higher scores.

To delve further into what is happening during the communication phase, we analyzed the evolution of players' signal repertoires throughout the game. While one important aspect of communication is to prevent a decline in expressiveness, another significant function is to promote alignment and the establishment of shared conventions (Clark, 1996; Hawkins, Frank, & Goodman, 2019). This understanding might account for the observed improvement in communication performance as the experiment progressed, as depicted in Figure 5, via the synchronization of individual combinatorial inferences into larger combinatorial systems. Figure 6C provides numerical support for alignment through the depiction of language similarity over time. To quantify alignment, we utilized the average DTW-based distance between pairs of the players' signal repertoires. The plot shows that the players had already begun to align their signals significantly even before the communication game began at game block 0. Our hypothesis is that alignment drives communicative accuracy, which is supported by the results presented in Figure 6D. The figure shows the correlation between communicative accuracy and signal repertoire alignment, suggesting that players with the most similar signals performed the best in the communication game.

Discussion and Conclusion

The combinatorial nature of symbol systems such as human language is critical to their effectiveness as tools for communication and cultural transmission (Kirby & Tamariz, 2022). Here we explored the idea that, similar to other language features such as compositionality (Kirby et al., 2015) or the structure of semantic category systems (Carr et al., 2020; Kemp et al., 2018), combinatoriality arises from the interplay of biological capacities, cultural evolution, and inductive biases amplified during transmission.

Our study suggests that combinatorial structure evolves to balance pressures for simplicity and informativeness in learning and use. To show this, we contrasted languages that evolve under communicative pressure and without, and found that only the former developed system-wide combinatoriality as they trade-off between the competing demands of learnability and communicative efficiency. Combinatorial systems achieve simplicity by relying on a small set of building blocks that are easy to learn and remember, while maintaining informativeness by recombining building blocks to produce a variety of discriminable signals. Our results provide further insights into the role of the communicative task and show that communication does not contribute to language simplification, but rather slightly increases the complexity of languages. One way to understand this finding is that simplification pressures during acquisition primarily affect whole signal systems, whereas speaker pressures during communication primarily affect individual signals. It is quite possible that individual signals became simpler during the communication phase, while the language as a whole actually became more complex. This is because signals can simplify in different directions. In this way, the simplification pressures acting on signals may actually be in tension with the simplification pressures acting at the language level, which is worth revisiting in future work. Rather than contributing to a loss of language complexity, then, the communicative task played two other important roles. It enabled simplicity pressures from the acquisition task to reduce complexity as much as possible without compromising signal discriminability, leading to informative systems that are well adapted to communication. In addition, it led to an alignment of players' individual combinatorial patterns into a larger, more synchronized system–shared conventions that helped players improve their communication performance.

Together, these results show how domain-general cognitive biases, such as inductive biases for simplicity, and functional constraints, such as pressures for informativeness that arise from communicative need, can shape communication systems and explain when and how design features like combinatorial structure in language might evolve.

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