

Simplicity and informativeness in the evolution of combinatorial structure

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Symbol systems—including language, music and pictorial diagrams—are crucial for the storage and transmission of human knowledge, ultimately underpinning our capacity for cumulative culture. A central feature underwriting these systems’ success is combinatorial structure: the reuse of building blocks to compose new concepts or ideas. Despite its apparent advantages, not all symbol systems rely on combinatorial structure, as evidenced for example by work emerging sign languages (Sandler, Meir, Padden, & Aronoff, 2005; Sandler, Aronoff, Meir, & Padden, 2011), indicating that combinatorial structures may only develop under certain conditions, rather than being an inherent property of symbol systems.

A body of recent work in evolutionary linguistics proposes that features like compositionality or systematicity, developed as efficient solutions to evolutionary trade-offs encountered in language acquisition and usage in cultural transmission (Kirby & Hurford, 2002; Kirby, Tamariz, Cornish, & Smith, 2015; Tamariz & Kirby, 2016; Christiansen & Chater, 2016; Smith, 2021). Such a framework might also account for the emergence of combinatorial structure, whose spontaneous emergence has previously been demonstrated across several domains (Verhoef, Kirby, & de Boer, 2014; Little, Eryılmaz, & de Boer, 2017; Lieck & Rohrmeier, 2021), but the mechanism by which it emerges from learning and use trade-offs remains unexplored.

In this study, we combine iterated learning with a communication game to directly test this *trade-off hypothesis* (Kirby & Tamariz, 2022), while concurrently exploring the role of pressures for communicative efficiency. We hypothesize that the communication task might not only lead to expressivity and help synchronize emerging patterns, but speaker-related pressures in communication may also contribute directly to signal simplification, over and above the learning process.

In our experiment, participants used a digital slide whistle to create signals for a set of visual referents. Two conditions are contrasted: one focused solely on learning and signal reproduction, without communication demands (“learning only”); another condition added a communication game after the learning phase (“learning plus communication”). During the learning phase, participants mem-

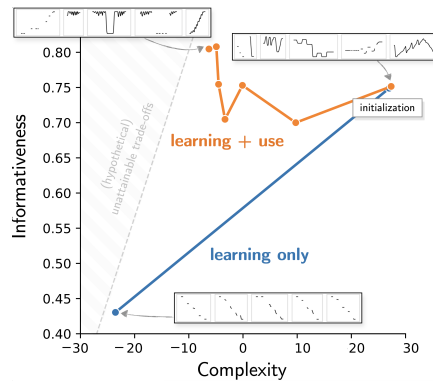


Figure 1. The figure compares the evolution of signaling systems under two conditions. Initially complex and informative (top right), systems evolve differently: without communicative biases ("learning only"), they become overly simple and less expressive. When learning is combined with communication, systems retain informativeness and simplify by developing combinatorial patterns, supporting the *trade-off hypothesis* that combinatoriality arises from balancing complexity and informativeness.

orized and reproduced five distinct whistled signals corresponding to five novel visual referents, which lacked any obvious compositional features that could lead to corresponding structures in the signal space. Signal-referent pairings were also randomized across generations to prevent predictable iconic associations. In the communication phase, participants in the "learning plus communication" condition were paired to play a reference game where they used their learned signals to refer to selected referents. This process was repeated across 15 chains of participants over five generations, allowing us to observe the evolution of the signaling systems under different conditions.

Consistent with the predictions of the trade-off hypothesis, our findings (see Figure 1) show that combinatorial structure only emerges when languages are subject to pressures from both learning and communication, marking this the first direct test of this theoretical prediction. While signals do become progressively simpler in the learning only condition, they do so to a point of losing discriminable features while not exhibiting marks of combinatoriality. Additionally, contrary to what a speaker-centered efficiency account might predict, speaker-related simplicity pressures in the communication did not contribute to overall language simplicity during the communication phase.

These findings indicate that combinatorial structures arise from the complex interaction of cognitive biases towards simplicity and informativeness, and align with the cultural evolutionary account of language development. Future research should explore the applicability of these results to different signal modalities and examine the computational basis of these biases through computational modeling.

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