**Discreteness and systematicity emerge to facilitate communication in a continuous signal-meaning space**

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Language relies on the interplay of many intricate features to ensure that the richness and complexity of human experience can be communicated in a tractable way. Two of these features are *discreteness* and *systematicity*. Discreteness provides a segmentation of inherently continuous phonetic and semantic spaces into distinguishable units and categories, while systematicity allows for these elements to be aligned in organized ways, ensuring that language is not only highly efficient but also predictably expressive.

Previous research has explored the emergence of these properties independently, highlighting the role of systematicity in language acquisition (Dingemanse, Blasi, Lupyan, Christiansen, & Monaghan, 2015), use (Nölle, Staib, Fusaroli, & Tylén, 2018), and its transmissibility and evolvability (Kirby, Cornish, & Smith, 2008). Conversely, work on discreteness has focused on its emergence in continuous signaling spaces along with combinatoriality (Verhoef, 2012; Little, Eryılmaz, & De Boer, 2017).

However, the question of how systematicity and discreteness arise jointly to support efficient communication — especially when *both* the signal and meaning spaces are continuous — and how these properties might constrain or reinforce one another, has been largely unexplored. In this study, we examine the concurrent emergence of these features in a two-player communication experiment where participants were asked to generalize learned continuous signals to communicate about a continuous color space. The signal space was whistled signals produced by an on-screen slide whistle interface, and the meaning space was defined by a subset of colors from the World Color Survey's standard color naming grid.

The experiment consisted of a learning phase and a communication phase. Participants learned 5 signal-color mappings. Five signals with a diverse set of perceptual features were selected from a larger set of signals collected by Hofer and Levy (2019), and their corresponding color referents were randomly selected to be approximately evenly spaced in hue. After learning, participants were paired up and asked to generalize those mappings to a larger set of color chips in a refer-

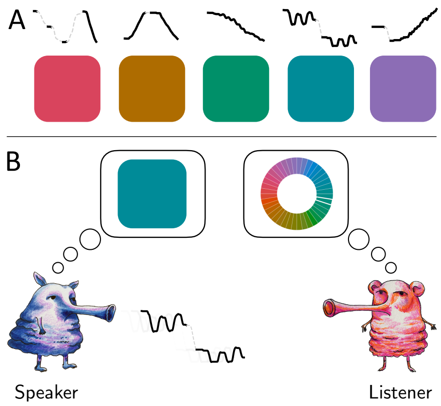


Figure 1. Our experimental framework. **A.** Initial color-signal pairings used in the learning phase. **B.** In the communication phase, speakers are presented with a target color and communicates it to the listener by generating a whistled signal. The listener guesses by selecting one of the 40 colors of the color wheel.

ence game. Our primary interest was in whether participants' extrapolated signals displayed elements of discreteness or systematicity in ways that supported successful communication. Discreteness was measured by calculating the cluster tendency of participants' signaling repertoires using the Hopkins statistic (Banerjee & Dave, 2004). Systematicity was measured by the correlation between pairwise signal distances (as measured using Dynamic Time Warping) and pairwise color distances in perceptually uniform CIELUV space (Schanda, 2007).

We found that participants learned to communicate successfully and aligned their signal repertoires, with more successful dyads showing higher degrees of alignment, suggesting that the formation of communicative conventions was crucial in driving communication performance. Furthermore, we observed the emergence of both systematicity and discreteness. However, we found that systematicity, but not discreteness, was correlated with better communication. Additionally, we note cases where participants seemed to have created composite signals to generalize to unseen colors, inviting speculation about the role of combinatoriality in this domain.

A few limitations of the present study include issues related to small-scale initializations in signal-meaning repertoires and limitations in measuring signal structure and similarity. Possible future extensions of this work are outlined, including investigating the role of discreteness and extending this setup to a multi-generational transmission experiment. Ultimately, we believe that these results contribute to a larger body of work exploring the role of human cognitive biases toward structure in the development and emergence of communication systems.

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