

THE COMPLEXITY OF A LANGUAGE IS SHAPED BY THE COMMUNICATIVE NEEDS OF ITS USERS: AN ITERATED HIERARCHICAL BAYESIAN MODEL

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Recent experimental and modelling work has found that languages are shaped by the referential context in which they operate (Müller, Winters, and Morin, 2019; Nölle, Staib, Fusaroli, and Tylén, 2018; Lupyan and Dale, 2010). Wray and Grace (2007) argues that even compositionality (the fact that the meaning of an utterance is a function of the meaning of its parts and the way in which these parts are combined) may have only evolved in response to changing social contexts. But how can the referential contexts of individual interactions come to shape the level of compositionality in the language of an entire community?

To explore these questions, we propose an iterated hierarchical Bayesian model that shows how partner-specific linguistic innovations can be generalized as community-wide features via a context-sensitive pathway. We combine insights from the approaches of Winters, Kirby, and Smith (2018) and Hawkins et al. (2021), manipulating reliability of context in pair-based interaction, while also considering abstractions of socio-linguistic knowledge at a higher, population-wide level. More specifically, an agent maintains a separate partner-specific representation of context for each communication partner, but a single overhypothesis about the distribution of types of contexts within the community, and a single community-wide distribution of possible languages. This setup allows an agent to dynamically adapt its language use to the communicative needs of individual partners, but also offers a mechanism for generalization of knowledge across different partners. We model communication between agents as an asymmetric reference game, where each agent is assigned the role of speaker or listener. Each game is split into multiple rounds in which the speaker is provided with a target meaning to convey and the listener is confronted with a context consisting of that target plus a number of distractors. An agent's type of context determines the semantic features in which the referents in any given context can differ for that agent. In a *one-feature-different context-type*, a single feature is sufficient for discriminating among all the referents in a context, and that feature is furthermore consistent across all rounds. In a *mixed context-type*, the meanings in any given context also

differ in one feature, but that feature differs on a round-by-round basis. Following the iterated learning framework (Kirby, 2001), agents in a generation observe data produced by speakers in the previous generation, then communicate with one another, with these processes being repeated for a large number of generations.

We first simulate a single-partner variant to evaluate our model's predictions against the experimental results of Winters, Kirby, and Smith (2015). In the *shared context* version, we assume that the speaker has direct access to the listener's context. We compare results to the *unshared context* version, where the speaker has uncertainty both about the context-type of the listener and which specific context the listener faces on any given round. In case of a shared context and one-feature context-type, we find the emergence of *one-feature languages* (i.e., which map all meanings sharing one of the features to the same signal), as these are the simplest communicatively functional in one-feature contexts. In the shared mixed context-type condition, the optimal strategy that guarantees communicative success leads to the emergence of *compositional languages* (i.e., which have consistent mappings for all features that make up the meaning). When context is not shared, speakers must infer the context-type of the listener over the course of interaction. This introduces an additional level of uncertainty, and it becomes a possibility for the speaker to design their utterance for the wrong context-type. Speakers are thus encouraged to produce more autonomous and less context-dependent utterances, generally resulting in the emergence of a higher proportion of compositional systems than in the case of a shared access to context.

We then examine the results for the multi-partner model. Where the speaker's communicative partners are homogeneous in facing one-feature or mixed contexts, the hierarchical model produces a similar pattern of results to the single-partner simulations: we find the emergence of languages that best compromise between ease of learning, adaptation to the homogeneous context-type, and robustness to uncertain inferences. However, we also find that the successive swapping of partners causes more overall uncertainty over context-types compared to the single-partner simulations, resulting in the emergence of more compositional languages. Furthermore, when a speaker interacts with partners with heterogeneous context-types, we find additional effects of this heterogeneity: when encountered partners have one-feature contexts, but differ in the specific feature that needs to be encoded for disambiguation, compositional languages become dominant, as speakers must compromise on using a language that encodes both features.

In sum, we show that the degree of compositionality that evolves in the language of a community is dependent on the communicative needs of its members, but also on the degree of uncertainty over the nature of those needs. Our model also tests the theory proposed by Wray & Grace for the emergence of compositionality, and finds that compositionality can emerge in communities where simpler languages would satisfy the individual needs of its users, as long as the community's needs as a whole are heterogeneous.

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