The emergence of word order and morphology in compositional languages via multigenerational signaling games

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Abstract

The experimental study of language change may provide novel insights into the nature of language, in particular on the role of cognitive biases and social processes in shaping grammatical and semantic structures. Here, we introduce multigenerational signaling games (MGSGs) as a new experimental paradigm for investigating how simple compositional languages emerge and change during transmission across generations in a diffusion chain, where each transmission step requires coordination between sender and receiver in a signaling game. We obtained three main results. First, we replicate and extend earlier findings by Moreno and Baggio suggesting that, in signaling games with fixed roles, mappings of signals to meanings tend to be transmitted from senders to receivers. We show that this holds for signaling games played in diffusion chains too, in which the receiver in one game becomes the sender in the next game. Second, we provide an experimental proof of concept that MGSGs are a viable laboratory model of cultural language change. Players consistently agreed upon a common signaling system after repeated signaling rounds, and the resulting code was effectively transmitted and gradually modified over generations. Third, we establish a baseline of results for further research using MGSGs. We found that the order of elements initially imposed on signals is largely maintained by successive generations. Moreover, the degree of coordination among players and the fidelity of inter-generational transmission exhibit a cumulative increase across generations. Finally, replicating a seminal result by Esper, we observed that morphological marking of semantic categories such as agent, action, and patient emerged gradually in the course of transmission.

Key words: language change; signaling games; iterated learning; diffusion chains; cultural transmission; compositionality; word order; morphology.

1. Introduction

A new theoretical framework has recently emerged in which languages are viewed as dynamical systems that change across individuals and over time (Beckner et al. 2009; Hruschka et al. 2009). Within this framework, novel hypotheses can be formulated as to how variation originates, and what constrains change. Language evolution may be shaped by principles of cognition (Christiansen and Chater 2008; Chater and Christiansen 2010), but it is an open issue at which stages of cultural
transmission such constraints play out: during language learning (i.e. during vertical transmission of languages from parents to offspring), during language use among peers (horizontal transmission), or when both of them are at play? Some changes may arise from individual processes of learning and development (Niyogi 2006), but as language is used for communication, its structure might, at some level, reflect the outcome of social coordination processes (Tomasello 1999, 2008; Croft 2009).

Here, we introduce a new laboratory model for studying whether and how properties of natural language are shaped by coordination and communication among peers, and by transmission across generations. The new model is a variant of the signaling game (Lewis 1969; Skyrms 2010; Moreno and Baggio 2015). We constructed diffusion chains with several participants (generations) playing two-person signaling games. In each game, signalers agree on a common code—a miniature language where signals refer to events. The common code is used by players in a new game (the next ‘generation’) as a basis for a new agreement, and so on throughout each diffusion chain. This iterative procedure allows us to track the evolution of referential codes across generations.

1.1 Cultural language change

In order to model language change, one must consider several interacting constraints, as languages change at nearly every level of their organization (Beckner et al. 2009). Recently, cultural transmission and social interaction have been viewed as the drivers of language change, reviving the central hypothesis of traditional historical linguistics (Greenberg 1959, 1963; Ringe and Eska 2013). In these new models (Kirby 2000), what characterizes transmission is that the input speakers receive as learning material is the output of other speakers who underwent the same acquisition procedure. Kirby et al. (2008) showed that compositionality emerges from iterated transmission cycles, where learners acquire and adapt the language based on the productions of previous generations. In other models (Hruschka et al. 2009), coordination, communication, and processing play a more prominent role (Pagel et al. 2007; Puglisi et al. 2008; Clark et al. 2008; Fedzechkina et al. 2012; Futrell et al. 2015).

Models of language change rest on three basic assumptions. First, for a linguistic form to spread, it has to be learnable. Second, learners should exhibit a bias, however weak, favoring that form (Culbertson 2012; Culbertson et al. 2012). Third, languages might change as the result of conflicting pressures on language users, such that speakers rely upon production economy, while hearers opt for clarity and explicitness (Cooper 1999; Christiansen and Chater 2008; Fay and Ellison 2013). Language change may occur during transmission, adapting to the cognitive constraints or biases that play out in language learning and use (Pagel et al. 2007, 2013; Dunn et al. 2011; Baronchelli et al. 2012; Dediu and Levinson 2012; Levinson and Gray 2012).

1.2 Iterated learning

Social learning is a basic ability underpinning cultural transmission (Tomasello 1999; Richerson and Boyd 2005). Humans have developed a capacity to learn from others that is essential for human uniqueness and ecological success (Boyd et al. 2011; Rendell et al. 2011). In studying language change as the result of social learning, the focus is the gradual modification of the language provided to a generation by the previous one. To investigate this process, a laboratory model called Iterated Learning was introduced.

Iterated Learning (IL) was first proposed as a model of language evolution, based on experimental and computational results showing that IL can lead to the emergence of compositional codes (for reviews, see Kirby and Hurford 2002, and Kirby et al. 2014). IL typically uses diffusion chains (Esper 1925; Bartlett 1932; Esper 1966). The first person in a chain is given some information, and attempts to reproduce it for the next person in the chain. The output is then passed on to the second person who undergoes the same procedure, and so on. Bartlett (1932) found that information became corrupted along the chain. Esper (1966) observed that, as a miniature language with a prespecified semantics is being transmitted over generations, morphological marking of semantic categories arises. Mesoudi and Whiten (2008) argue for the superiority of diffusion...
chains over more traditional single-generation memory experiments as a method for studying cultural transmission. IL has been applied in computer simulations (Kirby 2001; Smith et al. 2003; Smith 2004; Reali and Griffiths 2009; Swarup and Gasser 2009; Perfors and Navarro 2014) and experimental studies of birdsong (Fehér et al. 2009), stereotypes (Kashima 2000; Martin et al. 2014), and language (Kirby et al. 2008; see Caldwell and Millen 2008 for a review). IL reveals biases that can hardly be observed in studies with individual participants: weak biases in individuals may be amplified in a diffusion chain (Kalish et al. 2007; Kirby et al. 2007; Griffiths et al. 2008; Smith and Wonnacott 2010; Scott-Phillips and Kirby 2010; Galantucci and Garrod 2011; Galantucci et al. 2012).

Our model of language transmission, multigenerational signaling games (MGSGs), fits the general description of an iterated learning procedure, while at the same time also emphasizing the role of interaction between language users as a key mechanism of language transmission. Modeling suggests that interaction and feedback are important for language change (Steels 2003). Kirby et al. (2008) were among the very first to use diffusion chains to examine the relative balance between expressivity and learnability in languages. In their study, the semantic space consisted of twenty-seven combinations of object color, shape, and motion features. The first participant learned a set of word-to-object mappings, and had to generalize that mapping to novel objects by producing suitable labels. A subset of the labels produced by the first player was presented to the second as training material, who acquired the mappings and applied them to another subset of objects. Players never interacted, and were not aware they were part of a diffusion chain. The languages arising after a few generations were learnable, but ambiguous: some labels were used to signify different objects (Perfors and Navarro 2014; Kirby et al. 2015). In a second experiment (Kirby et al. 2008), this ambiguity was filtered out manually from the training data: the emerging codes were indeed compositional. This artificial filter was used as a substitute for communication. Recent work by the same group introduces communication directly into the IL scheme (Kirby et al. 2015). Two players are trained separately on an input language by observing mappings between words and their referents. Afterwards, they take turns as the speaker and listener in a series of communication rounds. The output language is used as a training set for the next generation. Communication is introduced within a generation. Still, there is no interaction-based transmission between generations. Unlike in the training of Kirby et al. (2015), however, language learning actually takes place by imitating, observing, and interacting with caregivers and peers.

1.3 Signaling games

Experimental research on dialog has produced a substantial amount of knowledge on the principles underlying language use (Clark 1996; Brennan and Hanna 2009). One upshot of this research is that, to understand the structure of languages, one needs to focus both on individual cognitive constraints and on social interactions. As suggested by the interactive-alignment model of dialog (Garrod and Pickering 2004; Pickering and Garrod 2004), convergence, in which the outputs of different speakers become similar, occurs when a speaker adjusts his behavior to the interlocutor’s for the purposes of efficient communication (Soliz and Giles 2014). Structural, phonetic, and morphological convergence have been observed (Seidenberg and Gonnerman 2000; Ferreira and Bock 2006; Beckner et al. 2016). Another line of work indicates that transmission is more effective in interactive situations (Tan and Fay 2011). Collaborative models propose that individuals interact to ensure that what is being said is agreed upon and properly understood by all parties. Therefore, meaning is bidirectionally negotiated. Clark and Wilkes-Gibbs (1986) found that dyadic conversational references are established over extended exchanges. Typically, these consist of cycles of interaction that are resolved only when there is mutual agreement on referents by both parties. An exchange often starts with idiosyncratic descriptions, and exploits subsequent interactions to adjust mismatching referents. Similar effects have been found in studies of the emergence of communication systems (Healey et al. 2007; Garrod et al. 2007, 2010; Theisen-White et al. 2011; Galantucci and Garrod 2011; for review see Galantucci et al. 2012). Brain areas that do not fully overlap with those involved in language processing are engaged during coordination and communication (Ramnani and Miall 2004; Carrington and Bailey 2009; Willems et al. 2010; Stolk et al. 2014). These results are consistent with an independent contribution of coordination and communication to linguistic structure.

In IL, participants acquire a miniature artificial language and are subsequently tested on their knowledge. Their output from the test phase is used as an input for the next participant. The model proposed here is similar, but acquisition and transmission are mediated by direct interaction among players, both horizontally (i.e. between sender and receiver) and vertically (when a receiver plays as sender in the next game). In our model, classical two-player signaling games (Lewis 1969;
Skyrms 2010) are therefore played iteratively in a diffusion chain. Signaling games are a simple yet highly flexible model of how agents update their beliefs based on observed signals and actions. In the simplest case, the sender has private access to a state of the world, and sends a signal to inform the receiver about it. The receiver then chooses an action in response to the signal. If the action is appropriate given the state (e.g., bring an umbrella, if it is raining), the trial is successful for both players. If the sender inconsistently uses a signal in a state and another signal in another state (a separating equilibrium), for arbitrary but equal numbers of states and signals), the receiver can always pick the appropriate action. Signaling game theory can be used to study information flow in networks of multiple players (Skyrms 2010) are therefore played iteratively in a diffusion chain. Signaling games are a simple yet highly flexible model of how agents update their beliefs based on observed signals and actions. In the simplest case, the sender has private access to a state of the world, and sends a signal to inform the receiver about it. The receiver then chooses an action in response to the signal. If the action is appropriate given the state (e.g., bring an umbrella, if it is raining), the trial is successful for both players. If the sender consistently uses a signal in a state and another signal in another state (a ‘separating equilibrium’, for arbitrary but equal numbers of states and signals), the receiver can always pick the appropriate action. Signaling game theory can be used to study information flow in networks of multiple players (Skyrms 2010), capturing a variety of real-world situations.

1.4 Aims of the present study

Our aim here is twofold. First, we provide a proof of concept that MGSGs are a viable laboratory model of language change. We show that (1) in signaling games, players converge on shared codes, and (2) these codes are transmitted and gradually modified over generations. Second, we establish a baseline of results for upcoming research with MGSGs. Here we use the simplest possible MGSG paradigm: feedback is complete, since both players simultaneously see at the end of a trial what state was seen by the sender and what response was given by the receiver; sender and receiver roles are fixed in a game (Moreno and Baggio 2015); the size of the state and signals spaces are limited and known to players; states are equiprobable for the sender; and signals are equiprobable for the receiver. MGSGs integrate horizontal and vertical transmission and therefore provide a valuable complement to previous IL research on vertical transmission (Kirby et al. 2008).

2. Experiment 1: word order

In the first experiment, we used stimuli (i.e. states in signaling games) similar to the visual scenes of Kirby et al. (2008). The aim of Experiment 1 was to obtain a baseline of results on the emergence of word order in the simplest possible version of MGSGs, with small sets of states and signals, fixed roles and complete feedback to players.

In both experiments reported here, seeding was used to initialize the diffusion chains. In seeding, the initial behavior or language is decided by the experimenter, and is then spread and modified by participants within the diffusion chain (Horner et al. 2006; Whiten et al. 2007; Flynn and Whiten 2010; Whiten and Flynn 2010; Nielsen et al. 2012). Diffusion studies aim at understanding how seeded patterns spread. In studies with adults, for whom cultural transmission is an established behavior, the question is how behavioral patterns change over time (Mesoudi and Whiten 2008). Studies of language transmission typically seed with random strings that denote ‘holistically’ (i.e. as fixed labels). This choice stems from theories of ‘proto-language’ as a holistic system (Wray 1998; Kirby 2000; Arbib 2005; Fitch 2007; Smith 2008). These theories suggest that proto-languages initially had proto-words for concepts, forming short, unstructured proto-word strings. This notion, however, is problematic. As Bickerton (2003) points out, it would be difficult for speakers to agree on meanings if utterances were holistic. Others suggest that early communication evolved from a proto-language more similar to actual language, albeit much simpler, with a proto-lexicon but no syntax (Bickerton 1990, 2003; Jackendoff 2002; Tallerman 2007). Bybee (2012) notes that grammatical structures are formed by the unification of simple elements, not by breaking complex elements apart. Therefore, if one’s aim is to demonstrate language change by cultural transmission, seeding with holistic codes may not necessarily be the most ecologically valid choice. Seeding with structured non-holistic codes, instead, has the advantage of steering clear from the question ‘what was there initially?’, as a plausible intermediate evolutionary state of language is used as a starting point of investigation. That is our approach here.

2.1 Methods

2.1.1 Participants

Thirty-six native speakers of Italian (mean age 23.5, age range 19–33 years, 24 females) were recruited for Experiment 1. They all had normal or corrected-to-normal vision, and all were trichromats. The sample size was based on previous iterated learning research (Kirby et al. 2008). Upon their arrival to the lab, participants were informed that they would play a game with a partner. Participants who played together in a game did not know each other beforehand. Participants were organized in four transmission chains of nine generations each.

2.1.2 Apparatus

Participants in a pair were seated in the experimental room at a large desk facing each other, so that each of them could not see the other during the session. Each player had their own workplace consisting of a
computer screen and keyboard. The screens were aligned back to back, rendering it impossible for each player to see their partner and their screen. Sender and receiver roles were assigned at the start of each session, and were fixed throughout a session. At the end of each game (generation \( n \)), the receiver became the sender in the next game (generation \( n + 1 \)), and diffusion chains were thus constructed. In between two sessions, the receiver was moved to the sender position, and a new participant was let into the room to play as the receiver.

2.1.3 Stimuli

We used the same 3-by-3 stimulus design as in Kirby et al. (2008). The states were visual scenes varying in three dimensions: shape (three types), color (three), and motion (three) (Fig. 1). We used artificial Tetris-like shapes and ambiguous hues to prevent players from transferring (partial) mappings of morphemes to meanings (e.g. ‘re’ to red) from their native language which may act as ‘focal points’ (preplay equilibria) in a game (Moreno and Baggio 2015). Objects were constituted by five squares. Motion trajectories (straight, curved, or zig-zaggy) of objects started and ended at the same spatial locations on the screen. Signal constituents were vowel-consonant monosyllables (Fig. 2). To prevent players from typing-in arbitrary strings, such as words from their native language, the labels had to be chosen by players (details below) from a set of nine shown on the screen. The task was to match the visual scenes resulting from the factorial combination of three feature sets (three features each: shape, color, motion; twenty-seven in total) to three-syllable strings as signals. For the sender, the task was to map scenes to signals, for the receiver the task was the reverse. We decided to let players choose among nine monosyllables to construct three-syllable signals, largely for practical reasons. First, in a multigenerational design all participants should be able to converge on a shared code, if data for a complete chain are to be collected: the state and signal space should be manageable in size, and pilot data suggested that larger vocabularies, as well as no limit on the number of elements in signals, yielded games that were difficult for some players. Second, our aim was to obtain a baseline of experimental results with the simplest possible version of MGSGs. Due to the flexibility of signaling games, a fuller exploration of larger state and signal spaces seems best suited for computational research.

2.1.4 Procedure

Participants were organized into four diffusion chains with nine players in each. Each player took part in two games (or sessions) of the experiment. In the first session, player A was the sender and B was the receiver (generation \( n \)). Once A and B had converged upon a mapping of signals to states, after a break a new game started, with B as sender, and C as receiver, establishing generation \( n + 1 \). No form of communication between players was allowed other than the signaling game. The experimenter was always present in the testing room.

Each signaling trial unfolds as follows (Fig. 2). The sender is privately shown a scene (1s clip) drawn randomly from twenty-seven possible combinations of shape, color, and motion, and sends a signal, denoting the event, to the receiver. To do so, the sender chooses three labels from the learned vocabulary: all nine labels are shown on a screen in a 3-by-3 grid (duration: self-paced), randomly arranged in each trial. The sender composes a signal, which is immediately sent to the receiver. Both players simultaneously see the signal the sender has composed. The receiver responds by composing the scene the sender might have seen, choosing shape, color, and motion features arranged in a 3-by-3 grid in a random order in each trial (duration: self-paced). Feedback (2s) is presented to both players indicating whether the elements that the receiver has chosen match the elements of the scene that the sender has seen. Studies of coordination games support the notion that feedback is important for the emergence of successful communication systems (Healey et al. 2007; de Ruiter et al. 2010). The game ends when participants reach sixty correct trials, with no constraint on the number of correct consecutive trials. A trial is correct if and only if all three features selected by the receiver in response to the signal match the features of the scene as seen by the sender.

We seeded chains as follows: the first sender in each chain (generation 1) was trained using a randomly generated bijective mapping of syllables to object features. In each training trial, the participant was shown an object, and had to compose the three-syllable string describing that object. Feedback was given as to which syllables and features were correctly or incorrectly matched in that trial. The order of syllables in all strings was imposed by the participant. The seeding material only included a vocabulary (a mapping of syllables to object features) but no ‘syntax’. Strings with a different order of elements (e.g. object-color-motion vs color-object-motion) could be correct so long as the actual constituent syllables matched the object’s features, regardless of order. The training was completed when the participant had learned all the associations, and performed correctly in three successive trials for each association. No time limit was set for this task.
2.1.5 Data analysis
We aimed to describe changes in code structure during transmission within chains. In particular, we tested for changes in the quality of code transmission and coordination, and innovation and fidelity in code structure. Importantly, because players learned a one-to-one mapping of syllables to meanings, compositionality is an inherent design solution here: players should only impose a linear order of elements in a signal (‘word order’) which is the structural dependent variable of interest in Experiment 1. Linear order was not imposed on signals by the experimenters: this was up to participants to decide and maintain.

We used five measures: structure, coordination, transmission, innovation, and asymmetry, as described below. We measured code similarity using mean normalized Levenshtein distances between the codes agreed upon by one generation, and the codes formed by the next generation, averaging over all meanings (Kirby et al. 2008). The normalized Levenshtein distance is defined as the smallest number of insertions, replacements, or deletions of characters required to transform one string into another, divided by the length of longest string. The output ranges from 0 to 1, where 1 is code identity.

Changes in structure (or compositionality) were measured using RegMap (Tamariz and Smith 2008; Tamariz et al. 2010), estimating how well a signal element consistently predicts a meaning element. A partial RegMap estimates how reliable the association between meanings and signals is. The full RegMap tests whether these mappings are bi-unique, returning a single value for the entire language. Higher scores suggest that similar meanings are consistently predicted by similar signals.

Coordination was measured by the mean normalized Levenshtein distance between codes for corresponding states used by sender and receiver in a game. Values range from 0 (no shared code) to 1 (common code). The coordination measure reveals how learnable a code may be, and to what extent an agreement on a shared code could be found in a game. An increasing coordination along a transmission chain suggests that codes become more learnable and more easily agreed upon by players.
Transmission measures the similarity between the codes used by the senders of two successive generations. As predicted based on earlier research (Kirby et al. 2008), transmission should increase along a diffusion chain if players restructure the code to render it more learnable and less error-prone.

Innovation describes to what extent the code acquired by the receiver of generation \( n \) differs from the code used by the same player when acting as the sender in generation \( n + 1 \). If the code becomes more learnable, innovation should decrease over generations (Legare and Nielsen 2015). Although innovation and transmission are often correlated, they are defined independently, and one is not the inverse of the other. Transmission describes how the codes change during transmission along a chain by comparing the codes of senders in generation \( n \) and generation \( n + 1 \). On the other hand, innovation tracks the changes introduced by the same player, comparing his behavior as receiver and as sender in two successive games.

We also measured role asymmetry between senders and receivers (Selten and Warglien 2007; McAvoy and Hauert 2015). In fixed-role games, receivers adjust their mappings more frequently, and senders tend to maintain their initial code, which then becomes the common code (Moreno and Baggio 2015). Our objective was to examine the division of labor in code transmission, and possibly replicate the findings of Moreno and Baggio (2015) in diffusion chains. Asymmetry is defined for a pair in a game as the number of code changes introduced by the sender minus the number of code changes introduced by the receiver, divided by the total number of code changes. A code has changed if a player uses a signal \( X \) to denote a certain visual scene in trial \( n \), and signal \( Y \) to denote the same visual scene in trial \( n + m \). The relevant code changes here concern mappings of scenes to signals (for the sender) and of signals to scenes (for the receiver). Hence, it is possible to track code changes for both sender and receiver even though the latter never produces any signals. Asymmetry ranges from \(-1\) (changes are introduced only by the receiver) to \(1\) (changes are made only by the sender). No particular asymmetry pattern strictly follows from having fixed roles in a signaling game, although the kind of informational asymmetry entailed by fixed role games can explain role asymmetry patterns (Moreno and Baggio 2015). A summary of our measures is shown in Fig. 3.

Players are free to use some or all syllables in various ways to denote scenes, so it is in principle possible that ambiguous languages would emerge, where a single syllable or signal has several meanings. We computed the mean number of syllables in each code across features in each dimension (shape, color, motion) to assess code expressivity.

We applied Page’s test (Page 1963) to assess change in all of the above measures over generations. Page’s test is used in data sets where the hypothesis that is being tested predicts a specific direction of effects. All analyses were carried out in MATLAB.

2.2 Results

We found no increase in structure across generations (Page’s test on RegMap: \( L = 858, P = 0.84 \)). From generation 1, in all chains, the codes were highly structured (\( M = 0.87, SD = 0.01 \)). Compositional codes from the first to the last generations were built based on a fixed linear order of constituents: e.g., the first syllable denoted the object’s shape, the second movement, and the third color.

Coordination was high from generation 1, and it increased over successive generations (\( L = 990, P = 0.01; \) Fig. 4a): codes became easier for players to agree upon along a chain. We found a slight increase of
transmission over generations ($L = 959, P = 0.04; \text{Fig. 4b}$): players in later generations were more accurate in transmitting the codes. Innovation did not decrease cumulatively ($L = 662, P = 0.312; \text{Fig. 4c}$). Although coordination and transmission have high values from the first generation, their evolution is not bound by ceiling effects: the observed values, averaged across generations, were significantly lower than ceiling (one-sample t-tests, $\mu = 1$, highest $P$-value 0.015).

We further explored what kind of changes participants were introducing in the codes. Of all changes 13 per cent were due to participants changing the order of the elements (‘word order’) in codes, 25 per cent arose from players remapping signal elements across semantic categories (e.g. using a former color word to denote a motion feature), and 63 per cent were remappings of syllable meanings within a semantic category.

Role asymmetry was negative (M = −0.6, one-sample t-test, $\mu = 0; t(35) = 35.9, P < 0.001$): receivers adjusted their mappings more often than senders did. Structural asymmetry (which player modifies word order) was also unidirectional, with senders imposing constituent order in signals (M = −0.85, one-sample t-test, $\mu = 0; t(35) = 24.7, P < 0.001$). Semantic asymmetry (which player modifies the mapping of scene features to signal elements) showed that senders were significantly less likely than receivers to change their mappings (M = −0.278, one-sample t-test, $\mu = 0; t(35) = 7.97, P < 0.001$).

In brief, in Experiment 1 we found that signals exhibit a compositional structure and a linear order from the first generation. Moreover, these characteristics are maintained by successive generations. Most code changes occurred within semantic categories. In addition, we show that codes tend to be transmitted from senders to receivers, thus replicating and extending previous results (Moreno and Baggio 2015).

3. Experiment 2: morphology

A major breakthrough in language evolution is the emergence of categories at various levels of linguistic organization (Garrod and Anderson 1987; Puglisi et al. 2008). In Experiment 2, our goal was again to track the evolution of structure over generations, now using a different set of semantic relations: not perceptual features (shape, color, motion) as in Experiment 1, but semantic roles for objects (agent and patient) and an action the objects are performing. A secondary aim of Experiment 2 was to determine whether the native language of players (Italian or Polish) affects codes. While recent work has revealed universal characteristics in human social interaction (Stivers et al. 2009; Dingemanse et al. 2015), natural languages vary in important ways. They make use of word order, inflection, and prosody to convey meaning. Certain languages rely more heavily on one or another grammatical device for specific purposes. Polish and Italian allow for relatively free word order (in Polish word order is largely free, while in Italian verb position varies within limits) but implement it using different linguistic devices: Polish has rich case-marking system; Italian cases exist only for pronouns.

3.1 Methods

3.1.1 Participants

Thirty-six native speakers of Italian (mean age 24.7, age range 19–30 years, 27 females) and thirty-six native speakers of Polish (mean age 22.3, age range 18–25 years, 22 females) took part in Experiment 2. We constructed eight transmission chains with nine generations each: four chains with Italian speakers, and four with Polish speakers. The sets of participants in Experiments 1 and 2 were disjoint.
structural asymmetry was unidirectional with senders imposing word order \((M = -0.71, \text{one-sample } t\)-test, \(\mu = 0: t(71) = 16.26, P < 0.001)\), whereas semantic asymmetry was equally influenced by both players \((M = -0.04, \text{one-sample } t\)-test, \(\mu = 0: t(71) = 1.55, P < 0.13)\).

We submitted average values across generations in each chain to an ANOVA using the speaker’s native language (Polish or Italian) as a between-subjects factor. There were no effects of L1 (Structure: \(F(1,8) = 2.33, P = 0.17\); Coordination: \(F(1,8) = 2.94, P = 0.13\); Transmission: \(F(1,8) = 3.34, P = 0.09\); Innovation: \(F(1,8) = 1.86, P = 0.22\)).

In five out of eight chains (three in Polish, two in Italian), players gradually modified the codes so as to mark syllables to denote different semantic categories: for example, all motions were mapped to syllables ending in ‘o’: ‘ro’, ‘to’, and ‘mo’ (Fig. 7a). This gradual change was confirmed by Page’s test \((L = 1282, P < 0.001)\) on the ratio between the number of morphologically marked signals and all signals in a generation, ranging between 0 (no morphological marking, e.g., random distribution of vowels in signals across semantic categories) and 1 (fully systematic morphological marking, e.g., as in Fig. 7b). This did not happen in Experiment 1, although signals were the same in both experiments.

### 3.2 Results

Compared to the first experiment, the task here was more difficult: players needed on average twenty-seven more trials to coordinate \((\text{Exp1: } M = 96, SD = 14.5; \text{Exp2: } M = 123, SD = 13.5)\). As in Experiment 1, compositional structure was present since generation 1 \((M = 0.85, SD = 0.02)\), and remained stable on a high level within a chain (Page’s test on RegMap: \(L = 608, P = 0.96\)).

As in Experiment 1, coordination \((L = 994, P = 0.013)\) and transmission \((L = 726, P = 0.01; \text{Fig. 6a and b})\) increased. The codes were becoming easier to transmit, and coordination between players was also easier. One difference between Experiments 1 and 2 was a decrease in innovation in the second study (Page’s Test: \(L = 716, P = 0.012; \text{Fig. 6c})\). Role asymmetry was negative \((M = -0.67, t(71) = 11.8, P < 0.001)\),

### 4. Discussion

The present study examined whether and how structure in simple artificial languages emerges and stabilizes in diffusion chains where players interact in signaling games. In two experiments, by introducing communicative pressure and feedback, we show that the emerging signaling systems are highly structured and expressive right from the first generation (Winters et al. 2015). We replicate earlier findings that language transmission tends to be unidirectional, from senders to receivers (Moreno and Baggio 2015), and we extend this to diffusion chains. We found an increase in coordination and transmission: it becomes easier over generations for
players to agree on a shared code, and codes become more similar over generations. In the second experiment, we observed the emergence of morphological marking, and a decrease in innovation over generations which was not seen in the first experiment.

Observations of how languages change may contribute to current discussions of the cognitive abilities underlying language acquisition. Garrod and Anderson (1987) have shown that, while interacting, partners align meanings through changes at different levels of form, including syntax (Branigan et al. 2000), prosody (Giles et al. 1991), and morphology (Beckner et al. 2015). Direct forms of semantic alignment, where players adopt the same labels of events, were also observed in modeling studies (Steels 2003; Barr 2004). Cuskley et al. (2014) showed using corpus data that languages change in a self-organizing way as the consequence of exogenous and endogenous pressures to minimize processing effort while maintaining a sufficiently high level of expressivity. One outstanding question is whether language change necessarily simplifies linguistic structure. Our Experiment 1 indicates that when codes are simple enough (i.e. there is compositional structure and linear order), there is no decrease in innovation over generations: the codes keep changing. Yet, in Experiment 2, where codes were more difficult to learn, we did find a cumulative decrease in innovation: codes changed until they were possibly perceived by players as optimal or ‘good enough’ in some respect.

A most intriguing finding in Experiment 2 is the emergence of morphological category marking. The codes resembled agglutinative languages: vowels denoted grammatical categories, and consonants denoted specific associations to items within a category. These results fit with the generalization proposed by Dressler (1985) that ‘there is a universal tendency to concentrate lexical meaning on consonants and grammatical meaning on vowels’ (for a discussion, see Maiden 1992). The systematicity that we found in the mappings between signals and referents is a putative language universal, and is present in the morphological structure of the lexicon (Monaghan et al. 2014). One of the functions of morphology is to mark grammatical relations. In Experiment 1, three dimensions (shape, color, motion) were easily distinguishable, and linear word order was sufficient to convey meaning. Comrie (1981) argued that basic morphology appeared at later stages of
grammar evolution. Heine and Kuteva (2002) suggest there was initially a distinction between verbs and nouns, and only with an increase in the complexity of the language system did morphology emerge. When strict word order is not enough to transmit ‘who did what to whom’ (agent and patient roles), speakers may use morphology to mark basic semantic distinctions. Grammaticalization theory describes how open-class lexical items may evolve into close-class grammatical items (Heine et al. 1991; Heine and Kuteva 2002, 2007). This may lead to morphologization, where an independent marker becomes an affix rather than a free word (Lass 1990; Anderson 2015). This kind of morphological category marking was among the first results produced by research on language transmission using diffusion chains: Esper (1966) had participants learn and produce names of colored (red or green) ‘nonsense shapes’; over successive generations, names were modified and by the last generation (of 44) the identity of shapes was marked by the initial or the final sound of a name (e.g. a final ‘a’ marked shape 1, an initial ‘v’ shape 2, an initial ‘p’ shape 3, etc.). Thus, in a ‘totally supple- system’ (Esper 1966), or a system with initial semantic but no morphological categories, morphological categories develop ‘in correspondence with the semantic categories’ (p. 579). Our results can be seen as a conceptual replication of these earlier findings.

What could account for the emergence of morphology? We suggest a possible reason is the facilitation of communication. In our second experiment, throughout a diffusion chain, vowels acquired the grammatical function of marking semantic relations. This decrease in arbitrariness is consistent with a recent revision of the notion that words have mainly arbitrary relations to their meaning (Monaghan et al. 2014). Dingemanse et al. (2015a) argue that a fully arbitrary language is difficult to learn. Our experiment suggests that grammaticalization during code transmission is relatively invariant and not necessarily tied to a speaker’s native language (Italian vs Polish) (Dingemanse et al. 2015b): regular linguistic forms, that parallel typological linguistic patterns, might emerge due to communication and transmission. Reali and Griffiths (2009) have shown in their computational work that a single generation of learners may not necessarily reveal a bias toward regularization: the bias appears after several generations with transmission, for example, because children are better at regularizing input languages than adults (Rische and Komarova 2016). In our experiment, grammaticalization was not evident in just a generation. Only after several generations did languages become regular and did proto-morphology emerge.

5. Conclusion

In this article, we described two experiments on language transmission using signaling games. We obtained three main results. First, we replicated and extended the findings by Moreno and Baggio (2015), showing that codes tend to be transmitted from senders to receivers also in signaling games played in diffusion chains (MGSs). Moreover, we show experimentally that MGSs are a working laboratory model of cultural language change: codes are gradually modified in the course of transmission; however, players effectively coordinate on a common code and can use it in communication. Finally, we establish a baseline of results for further research using MGSs. Specifically, we found that the order which is initially imposed on signals is largely maintained by successive generations. Still, morphological marking of semantic categories such as agent, action, and patient gradually emerged during transmission. Our study suggest that aspects of language change can be studied experimentally in the laboratory using the same class of game theoretic models employed in philosophy, biology, and economics to analyze coordination behavior in populations of agents.

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