SYNTHETIC MODELING OF CULTURAL LANGUAGE EVOLUTION

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Recently cultural theories of language evolution have gained significant momentum in explaining natural language. This paper reviews agent-based modeling, one of the key methodologies which is in part responsible for these developments. We discuss the most important challenges for a theory of cultural language evolution and the resulting dominant experimental paradigm. The discussion is framed along examples of experiments conducted within the methodology. We focus, in particular, on spatial language as an example of a complex and cognitively central domain treated in a series of robotic experiments.

1. Cultural Theories of Language Evolution

Cultural theories of language evolution trace, explain and model the cultural development of the languages of the world. Explaining both the past and present of language is a daunting goal. The languages of the world have developed into ingenious systems for communicating enormous subtleties about the inner and outer world. An example of a part of language in which this creativity is very tangible is spatial language (Levinson, 2003; Svorou, 1994; Levinson & Wilkins, 2006). We know now from different studies in spatial language that human languages vary tremendously in how people, for instance, talk about the spatial configuration of objects. The following phrase from Tzeltal which is a Mayan language shows an example of a geocentric spatial language strategy (Brown & Levinson, 1993).

(1) *ay* *ta* *ajk'ol* *te* *limite*
EXIST PREP 'uphill' the bottle (= Figure)
'The bottle is to the uphill (i.e., south)'

Typologists tell us that languages differ on two levels of organization: *language systems* and *language strategies*. They call systematic subparts of language – systems. For instance, the English proximal spatial relations system consists of two spatial relations "near" and "far". The Spanish proximal system, on the other hand, features three relationships (Kemmerer, 1999). But languages also differ more drastically in the kinds of strategies they support. Tzeltal, for instance, has no lateral projective system. Other paradigmatic differences can be observed in the syntactic strategies a language supports. Spatial relations in some languages are expressed using verbs, particles or adpositions whereas in German or English adjectives and prepositions are the most important devices.

2. Methodologies

Cultural theories of language have to account for these vast differences. Three main methodological tools which are used to study the cultural origins of language 1) linguistic fieldwork and typology 2) experimental psychology and 3) agent-based modeling. We briefly discuss these three in the following paragraphs.

Linguistic research into the cultural origins of language is primarily driven by two sources of data historical and synchronic. Historical data of language change can be used to trace lexicalization, grammaticalization (Hopper & Traugott, 2003) and creolization processes (Mufwene, 2001) that organize language change. From the data, researchers hypothesize cognitive operations and strategies that orchestrate language change (Heine, 1997). A third source of evidence is synchronic. Comprehensive typological surveys of the languages of the world (Haspelmath, S., Gil, & Comrie, 2005) have revitalized comparative typology and given rise to radically new cultural theories of the origins of language (Evans & Levinson, 2009).

A second big methodological paradigm is rooted in experimental psychology. Galantucci and Garrod (2011), for instance, propose "semiotic experiments" in which human subjects are developing a communication system from scratch. The main manipulation is to prevent the interlocutors from using the language, e.g. English, they already know. These experiments reveal the strategies humans use, in order, to arrive at shared communication systems. Others are interested in how properties of the transmission system affect the emergence of linguistic phenomena (Scott-Phillips & Kirby, 2010) .

The third paradigm and the main focus of this papers is agent-based modeling. Simulated or robotic agents form communities which are put under communicative pressure to solve problems in their environment using language. The experiments start when the experimenter implements a particular proposal of cognitive strategies for learning and formation of language into each agent of the population. The population then goes through a sequence of interactions simulating the emergence of language systems in populations of artificial agents.

3. Language Games

One way to frame agent-based modeling is by using *language games* (Steels, 2001). A language game is a routinized turn-taking interaction. Each agent can take the role of speaker and hearer in such an interaction. Agents share a cooperative goal, the restricted real world context, and the possibility of non-verbal communication, for example through gestures or joint action.

An example of a particular language game is the *spatial language game* (taken from Spranger & Steels, 2012) in which two humanoid robots talk about objects in their environment. The robots try to draw each others attention to objects in the vicinity using language. The set-up is exemplarily shown in Figure 1. The environment consists of a number of blocks of equal size and color (circles), a box (rectangle) and the interlocutors (arrows). The vision system of each robot tracks objects in the vicinity and establishes a model of the environment consisting of blocks (circles) with real-valued distances and orientations of objects with respect to the body of the robot. The environment is open-ended. New blocks, boxes and robots are added or removed and their spatial configuration changed.

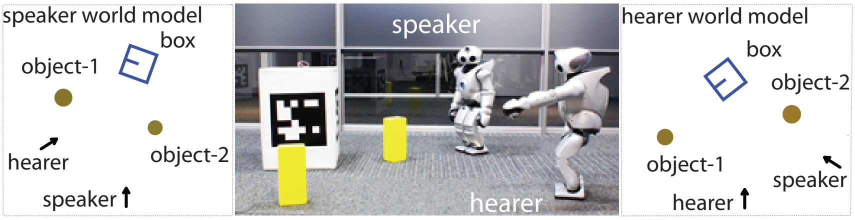

Figure 1. This figure shows the set-up for spatial language game experiments. The images left and right show the internal situation model as perceived by each robot.

1. Each agent perceives the environment after both have established a joint attentional frame (Tomasello, 1995).

2. The speaker randomly selects an object from the situation model. Suppose he picks one of the blocks, e.g. `object-1`.

3. He conceptualizes a meaning which enables him to single out the topic from the rest of the objects in the context. For instance, he could pick discriminating features such as color, size, object type. In the situation in Figure 1 neither color nor size distinguish between the two blocks, so agents might use compositional spatial semantics and combine a spatial relation “in front of” with a reference objects such as “the box”.

4. When the speaker successfully constructed a semantic program, he goes on to verbalize his conceptualization of the topic object. Verbalization is a complex process in which the agents make choices about how to express the semantic program. For instance, the speaker might choose to leave certain aspects unexpressed because the language offers no syntactic vehicles to express them or because they are obvious given the context. Once the speaker constructed a string of words it is passed to the hearer.

5. The hearer recovers as much as possible from the semantics underlying the utterance possibly representing semantic ambiguity.

6. This is followed by a process of active interpretation in which the hearer tries to reconstruct the conceptualization the speaker had in mind. This process integrates as much knowledge as possible from the current context to constrain the possible interpretation of the utterance.

7. When the hearer found a possible topic of the phrase, he points to it.

8. The speaker checks whether the hearer points to the object he had in mind when uttering the phrase. If the hearer pointed correctly the game is a success and the speaker signals this outcome to the hearer. If the game is a failure, the speaker points to the topic.

After such an interaction both agents have established success or failure and can update their internal linguistic and conceptual repositories, in order, to be more successful in the future. Agents continuously interact using these scripts and gradually develop adequate syntactic and conceptual means to express themselves. They start with a set of operators that are hypothesized to be necessary and sufficient for seeing the emergence of possible language strategies to be successful in the language game. The agents then play a series of games where they configure possible strategies and try them out. What is not put in these agents are concrete choices, neither for the conceptual building blocks used to formulate meanings (steps 3 and 6), nor for the linguistic choices that they should use to express those meanings (steps 4 and 5), because the goal is to show how these emerge through collective invention and negotiation.

Language games such as the spatial language game are designed with a three important ideas in mind which often (at least in part) overlooked or missing from other approaches.

open-endedness Language is an open system. New technological advances, changing environmental conditions and new topics force communities to expand and adapt their language. For instance, in spatial language games new blocks and boxes can enter the scene and the spatial configuration of objects and robots is constantly changing.

no central coordinator Language is not designed top-down by a central authority that enforces certain conventions. Rather language evolves decentralized. Conventions are typically established locally in small subgroups of the population. For instance, in spatial language games always two agents interact. Any new word or convention established between the two interlocutors still has to stand the test against conventions established between other agents of the population.

no telepathy Language conveys hints at how the speaker conceptualizes reality but it does so without allowing interlocutors direct access to each others internal representations. An utterance conveys pointers or parts of the way the speaker construed the world and the rest has to be actively reconstructed by the hearer against the background of the shared context. So when an agent guesses the meaning of a new word he might be uncertain about the exact meaning and he can make mistakes.

4. Examples of Agent-based Studies

Models in the agent-based paradigm have seen increases in complexity both in terms of semantic and syntactic strategies emerging in experiments. A lot of work initially focussed on perceptually grounded lexicons. Prime domains are color (Steels & Belpaeme, 2005), actions (Steels & Spranger, 2008) and naming (Steels & Loetzsch, 2012). In these experiments, agents co-evolve an ontology of categories (or names) together with a lexicon for expressing these categories. Spatial language has also been treated in this way. Figure 2 shows the dynamics of an experiment in which agents develop a system of projective spatial relations (e.g. front, back, left, right). Agents start without any categories and words (number of construction). Over the course of many interactions, new categories are invented and shaped so as to provide the community with a sufficiently shared lexical system so that communication is successful.

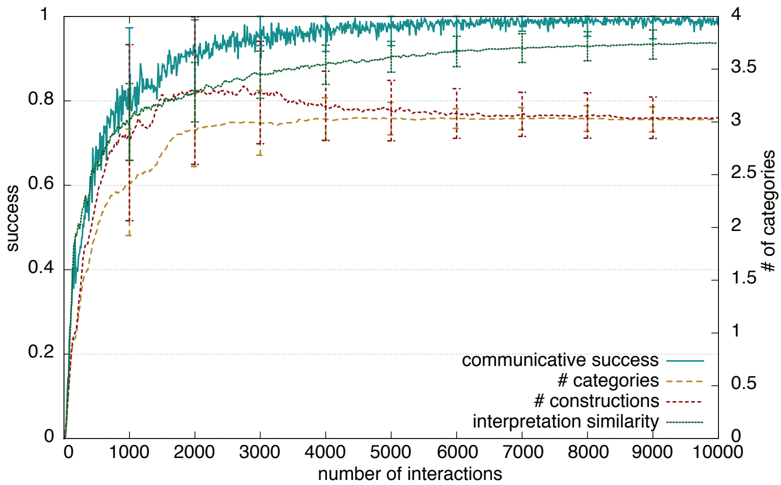

Figure 2. Dynamics of 10 agents interacting in 10000 interactions (multiple trials). The graph shows how communicative success increases with the number of categories and word (constructions) invented and spreading in the population.

In a second step the complexity of meanings was increased, for instance, by using predicates with arguments (Steels & Loetzsch, 2008). Recently, the full complexity of human language semantics is being tackled by using a procedural approach to meaning and by operationalizing basic insights from cognitive semantics (Spranger, Pauw, Loetzsch, & Steels, 2012). These new technological advances allow to study the conventionalization of compositional meaning. Something which so far has received little attention and opens the door for (cultural) evolutionary explanations of conceptualization strategies like the absolute systems of uphill-downhill relations in Tzeltal (see Example 1). First step in this direction show promising results. For instance, Figure 3 (from Spranger, 2011) shows the dynamics of a population which at the same time as building an ontology and lexicon is actually negotiating the conceptualization strategy with which to build the system. Depending on the environment these populations develop proximal (e.g. near, far), projective (front, back) or absolute systems (north,south). In these experiments *discriminative power* is an important factor that determines which system evolves. If there is a global landmark consistently available in many scenes and useful for distinguishing objects then an absolute system develops.

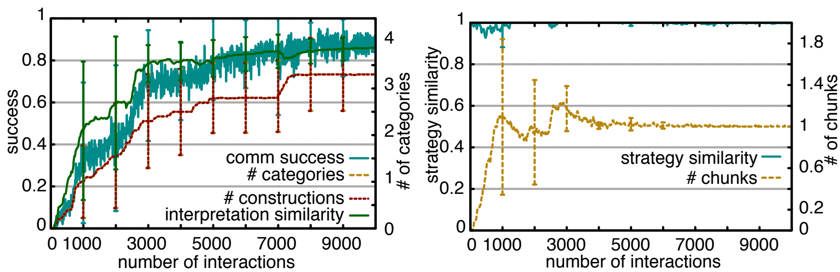

Figure 3. The left image shows the development of success and categories. The right image shows the average number of spatial conceptualization strategies in the same populations (number of chunks). While building a systems, the agents are negotiating which strategy to use.

Finally, the complexity of the syntactic aspects of the evolving languages increases. There are now experiments in which predicate-argument structure and associated problems of search (Steels & Wellens, 2006), semantic ambiguity (Spranger & Steels, 2012) and cognitive effort (Trijp, 2008) are researched. To illustrate this approach, let us consider an example from spatial language (from Spranger & Steels, 2012). The following two phrases are from German.

(2) *der* *linke* *Block*
the.NOM left.ADJ.NOM block.NOM
'The left block',

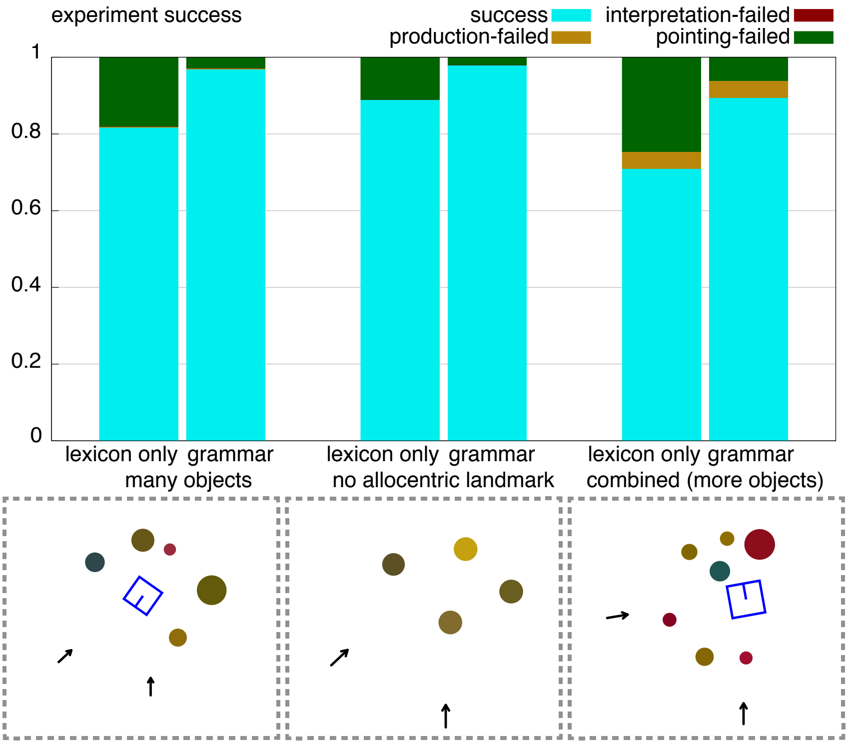

Figure 4. Comparison of lexicon only populations versus populations that are operating a German locative grammar.

(3)	*links*	*des*	*Blockes*
	left.PREP.GEN	the.DET.GEN	block.GEN
	‘to the left of the block’,		

Both of these phrases use the same lexical material, but they differ drastically in their grammatical structure. Importantly, these differences in syntax convey subtle differences in semantics. The use of the relation *left* as adjective (Example 2) signals a different construal of reality than the use as preposition (Example 3). In other words, these two phrases have different interpretations which are signaled by their syntactic structure. An agent which only knows the lexicon and is confronted with any of such phrase has to resort to the context to disambiguate the different possible interpretations.

Agent-based models allow us to quantify the impact of grammar. Figure 4 shows a comparison of results from populations which feature only a German lexicon and a population which operates a full German locative grammar. The graph shows a clear communicative advantage for the population with grammar. This fact can be exploited in subsequent grammar formation experiments in which agents start from a lexicon-only stage and develop a system of grammatical markers.

5. Discussion

Agent-based models are seeing an increasing coverage in books (Cangelosi & Parisi, 2002; Lyon, Nehaniv, & Cangelosi, 2007; Nolfi & Mirolli, 2010; Steels, 2012). This is probably due to the important advantages of the agent-based methodology. The most important of these is that any proposal has to be sufficiently specific to be implemented in a computer or on a real robot. As a consequence, every proposal, every instantiated theory that is shown to work using agent-based modeling can immediately be accepted as a coherent and stringent proposal that (at least in principle) reveals all underlying assumptions and provides reproducable and testable dynamics. This is no small achievement. Many theories or contemplations about language evolution are described in textual form without any formalization. While such theorizing is a natural step in any scientific discipline it should only be an intermediate step which is accompanied by or triggers the acquisition of additional data and results from other methodologies.

Ideally, modeling helps us to 1) make implicit assumptions explicit, 2) test theories for coherence and consistency, 3) allow for manipulation of model conditions which are difficult to manipulate with humans and 4) generate new hypotheses. Language game modeling is no exception but it adds an additional point. Because of the realistic setups, any working experiment immediately provides us with actual artificial systems that can interact and evolve language in the real world.

In our view robotic models occupy a special place in agent-based modeling. These models 1) are immediately insightful with respect to foundational problems such as *symbol grounding* (Steels, 2008), 2) they increase the realism of experiments (Loetzsch & Spranger, 2010) and 3) they lead to mechanisms and algorithms robust against noise in perception (Spranger & Pauw, 2012). Every simulation makes assumptions about the structure and behavior of the simulated world. Inadvertently, many of these assumptions are implicit. Experiments in the real world also make implicit assumptions, but, showing that something works in the real world is an obvious existence proof and requires less further justification of assumptions and methods. Just as a hypothesis which is tested in a simulated model gains in validity and justification, so does a model when it stands the test of reality.

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References

Brown, P., & Levinson, S. (1993). ”uphill” and ”downhill” in tzeltal. *Journal of Linguistic Anthropology*, *3*(1), 46–74.

Cangelosi, A., & Parisi, D. (Eds.). (2002). *Simulating the evolution of language.* Springer.

Evans, N., & Levinson, S. C. (2009). The myth of language universals: Language diversity and its importance for cognitive science. *Behavioral and Brain Sciences*, *32*(05), 429-448.

Galantucci, B., & Garrod, S. (2011). Experimental semiotics: a review. *Frontiers in Human Neuroscience*, *5*.

Haspelmath, M., S., D. M., Gil, D., & Comrie, B. (2005). *The world atlas of language structures.* Oxford University Press.

Heine, B. (1997). *Cognitive foundations of grammar.* Oxford University Press.

Hopper, P. J., & Traugott, E. C. (2003). *Grammaticalization.* Cambridge University Press.

Kemmerer, D. (1999). ”Near” and ”far” in language and perception. *Cognition*, *73*(1), 35 - 63.

Levinson, S. C. (2003). *Space in Language and Cognition: Explorations in Cognitive Diversity.* Cambridge University Press.

Levinson, S. C., & Wilkins, D. (2006). *Grammars of Space.* Cambridge University Press.

Loetzsch, M., & Spranger, M. (2010). Why robots? In A. Smith, M. Schouwstra, B. de Boer, & K. Smith (Eds.), *The evolution of language (evolang 8)* (pp. 222–229). Singapore: World Scientific.

Lyon, C., Nehaniv, C. L., & Cangelosi, A. (2007). *Emergence of communication and language.* Springer.

Mufwene, S. (2001). *The Ecology of Language Evolution.* The MIT Press.

Nolfi, S., & Mirolli, M. (2010). *Evolution of communication and language in embodied agents.* Springer.

Scott-Phillips, T. C., & Kirby, S. (2010). Language evolution in the laboratory. *Trends in Cognitive Sciences*.

Spranger, M. (2011). Recruitment, Selection and Alignment of Spatial Language Strategies. In T. Lenaerts, M. Giacobini, H. Bersini, P. Bourgine, M. Dorigo, & R. Doursat (Eds.), *Advances in artificial life, ecal 2011: Proceedings of the eleventh european conference on the synthesis and simulation of living* *systems,.* MIT Press.

Spranger, M., & Pauw, S. (2012). Dealing with Perceptual Deviation - Vague Semantics for Spatial Language and Quantification. In L. Steels & M. Hild (Eds.), *Language Grounding in Robots.* Berlin: Springer-Verlag.

Spranger, M., Pauw, S., Loetzsch, M., & Steels, L. (2012). Open-ended Procedural Semantics. In L. Steels & M. Hild (Eds.), *Language Grounding in Robots.* Springer.

Spranger, M., & Steels, L. (2012). Emergent Functional Grammar for Space. In L. Steels (Ed.), *Experiments in Cultural Language Evolution.* Amsterdam: John Benjamins.

Steels, L. (2001). Language games for autonomous robots. *IEEE Intelligent systems*, 16–22.

Steels, L. (2008). The symbol grounding problem has been solved. so what's next? In M. de Vega (Ed.), *Symbols and embodiment: Debates on meaning and cognition.* Oxford University Press.

Steels, L. (Ed.). (2012). *Experiments in Cultural Language Evolution.* John Benjamins.

Steels, L., & Belpaeme, T. (2005). Coordinating perceptually grounded categories through language: A case study for colour. *Behavioral and Brain Sciences*, *28*, 469–529.

Steels, L., & Loetzsch, M. (2008). Perspective alignment in spatial language. In K. Coventry, T. Tenbrink, & J. A. Bateman (Eds.), *Spatial language and dialogue* (pp. 70–88). Oxford University Press.

Steels, L., & Loetzsch, M. (2012). The grounded naming game. In L. Steels (Ed.), *Experiments in Cultural Language Evolution.* Amsterdam: John Benjamins.

Steels, L., & Spranger, M. (2008). The robot in the mirror. *Connection Science*, *20*(4), 337-358.

Steels, L., & Wellens, P. (2006). How grammar emerges to dampen combinatorial search in parsing. In P. Vogt, Y. Sugita, E. Tuci, & C. Nehaniv (Eds.), *Symbol grounding and beyond: Proceedings of the third international workshop on the emergence and evolution of linguistic commun* (pp. 76–88). Springer.

Svorou, S. (1994). *The grammar of space* (Vol. 25). John Benjamins.

Tomasello, M. (1995). Joint attention as social cognition. In C. Moore & P. J. Dunham (Eds.), *Joint attention: Its origins and role in development.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Trijp, R. van. (2008). The emergence of semantic roles in fluid construction grammar. In K. Smith, A. amd Smith & R. Ferrer i Cancho (Eds.), *The evolution of language (evolang 7)* (pp. 346–353). Singapore: World Scientific Publishing.