Recruitment, Selection and Alignment of Spatial Language Strategies

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Abstract

All languages of the world have a way to talk about space and spatial relations of objects. Cross-culturally, immense variation in how people conceptualize space for language has been attested. Different spatial conceptualization strategies such as *proximal*, *projective* and *absolute* have been identified to underlie peoples conception of spatial reality. This paper argues that spatial conceptualization strategies are negotiated in a cultural process of linguistic selection. Conceptualization strategies originate in the cognitive capabilities of agents. The ecological conditions and the structure of the environment influence the conceptualization strategy agents invent and which corresponding system of lexicon and ontology of spatial relations is selected for. The validity of these claims is explored using populations of humanoid robots.

Introduction

Human language is a complex adaptive system (Beckner et al., 2009), which is shaped by its users in a process of cultural evolution in order to achieve communicative goals such as drawing the attention to an object in the environment using spatial language. Language evolves constrained by factors such as communicative success, expressivity, learnability and ecological significance. This paper argues that these claims are also true for spatial language and that they are at the heart of explanations for the diversity of spatial language attested across different cultures.

Spatial language exhibits enormous amount of cross-cultural variation on two levels.

Spatial language systems Spatial language is typically a conglomerate of different systems. English for instance has a *proximal* system consisting of the two spatial relations “near” and “far”, a *projective* system including relations such as “left” and “front”. Moreover, English features an *absolute* system of spatial relations, e.g. “north” and “east”. Languages differ with respect to the particular organization of language systems. Spanish, for instance, features three proximal relations (Kemmerer, 1999).

Spatial language strategies Languages differ qualitatively in the kind of systems they support. For instance, some languages such as the Mayan language Tenejapan do not have projective terms but only absolute spatial relations (Levinson, 2003). Speakers of this language conventionally refer to objects in the immediate vicinity as *uphill* or *downhill*. Tenejapan speakers, therefore, habitually conceptualize reality differently than speakers of English.

There are two questions immediately following from this observation: (1) how do language systems form, (2) what are the origins of strategies. If one wants to study the evolution of spatial language, answers to the origins and development of both layers of language change have to be identified. Previous work has shown how language strategies can form language systems, e.g. for color and actions (see Steels, 2011 for an overview). In these experiments, agents are a priori endowed with a particular language strategy which includes a way of construing reality plus a battery of language change operators. The experiments then show that given these prerequisites autonomous agents can negotiate a particular system of categories (ontology) and words (lexicon).

Recently the origins of language strategies themselves have come under investigation. Bleys (2010) proposes that color strategies are under selective pressure driven by communicative success and cognitive effort (see also van Trijp, 2010 for a similar argument). This paper broadens this approach by extending it to spatial language and, most importantly, by proposing a concrete account of the origins of language strategies. Three important concepts guide our discussion (Steels, 2011).

Recruitment Language strategies are grounded in general cognitive capabilities and operations (Steels, 2007). For instance, the absolute strategy in English requires that agents are able to categorize objects using spatial categories that relate to particular geocentric features of the environment. In English absolute system this is related to compass readings and map use (Tenbrink, 2007). In other languages such features can include geocentric landmarks such as mountains which are always visible, or other global features such as the aforementioned uphill-downhill distinctions (Levinson, 2003). The categorization of these objects themselves is a cognitive ability that needs to be present before a linguistic absolute spatial system can form. Cognitive operations are recruited and assembled to form spatial conceptualization strategies.

Selection Once a strategy has formed it is used to build a concrete system of spatial categories and linguistic means to express them. For instance, in the simplest case a strategy is expressed lexically by naming the spatial relations. The system and the strategy are both subject to selective pressures. Other strategies might compete in terms of success, expressivity and ecological significance. To organize competition and selection, the overall success of a strategy and the associated ontology and lexicons are tracked.

Alignment Language is a phenomenon that occurs in the interactions of individuals of a group of language users. Language strategies or any linguistic material are invented in local interactions in which typically few members of a population participate. Different parts of the population might invent other strategies. This poses a problem as for language to be usable it needs to be conventionally used and known to the complete population. Alignment is the process by which a strategy and the corresponding language systems spread in the population. We organize alignment of strategies using the scoring of strategies used for orchestrating selection and competition.

This paper gives a mechanistic account of the origins and evolution of spatial language strategies by identifying concrete cognitive operations, selection and alignment mechanisms. We defend the main claim using artificial language evolution experiments which have been a key technique to identify, explore and validate ideas about cultural language evolution (Steels, 1995; Kirby, 2002; Smith et al., 2003).

Adaptive Spatial Language Games

For researching the basic claims of this work, we setup experiments in which robotic agents (Sony humanoid robots, see Fujita et al., 2003) encounter objects in spatial scenes. Such setups are called *spatial language games* and they package a specific intention – talking about objects in the environment – with a specific interaction script.

Figure 1 shows the environment in which two robots interact. Both robots are equipped with a vision system that singles out and tracks objects (Spranger, 2008). The environment contains four types of objects: *blocks*, *boxes*, *robots* and *geocentric markers*. The vision system extracts the objects from the environment and computes a number of raw, continuous-valued features such as *x*, *y*, *width*, and *height*, but also color values in the YCrCb color space.

Always two agents randomly drawn from a population interact, one acts as the speaker, the other as the hearer. The spatial language game uses the following game script assuming a population P of agents, and a world consisting of a set of individual objects.

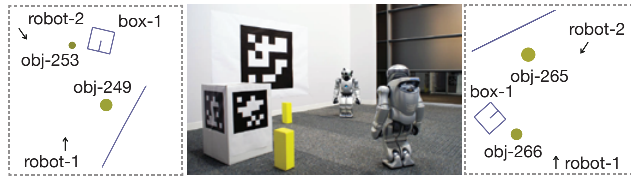

Figure 1: Spatial setup. To the left the world model extracted by the left robot is shown. To the right the same for the other robot is depicted.

1. The speaker selects an object out of the context, further called the topic T.
2. The speaker tries to find a meaning comprised of a particular spatial relation and a particular way of conceptualizing reality for describing the topic.
3. The speaker looks up the word associated with the spatial relation in his memory and produces the word.
4. The hearer looks up which relation is associated with this word in his memory and examines the context to find a unique object which satisfies the relation.
5. The hearer points to this object.
6. The speaker checks whether the hearer selected the same object as the one he had originally chosen. If they are the same, the game is a *success* and the speaker signals this outcome to the hearer.
7. If the game is a *failure*, the speaker points to the topic T he had originally chosen.

Such an interaction can fail for different reasons. For instance, the speaker might be unable to discriminate the topic object because he is missing a spatial relation or a conceptualization strategy. Both success and failure of communication provide opportunities agents to adapt their linguistic knowledge, ontologies and repertoires of conceptualization strategies.

Grounded Spatial Conceptualization Strategies

We use a computational formalism called *Incremental Recruitment Language* (IRL) that was specifically developed for representing adaptive conceptualization strategies (Spranger et al., 2010) and spatial semantics. To make this more concrete let us consider the semantics underlying a specific spatial phrase. Figure 2 shows the representation of the spatial semantics of a phrase like "near the box" which consists of a spatial relation (near) plus additional information about the landmark (the box).

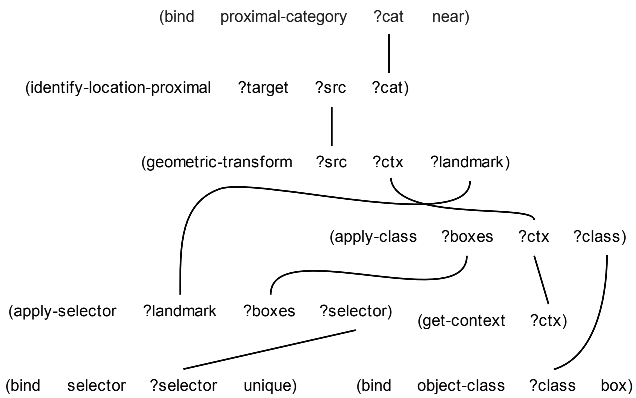

Figure 2: IRL-program representing the semantic structure of the phrase "near the box".

The main idea behind IRL is that semantic structure is procedural (Johnson-Laird, 1977) and can be represented using programs (IRL-programs). Consequently, we represent the semantics of the phrase as a set of cognitive operations such as applying a categorization (`identify-location-proximal`), and transform the viewpoint on the scene to a specific object (`geometric-transform`) that are linked in a certain way. For instance, the output of the operation `geometric-transform` linked by the variable `?src` (all variables start with a `?`) is connected to the input of the categorization operation. In other words, once the set of objects from the context (introduced by `get-context`) is transformed to a particular viewpoint then the spatial category is applied.

The following operations (excerpt) are used as building blocks for spatial conceptualization strategies.

geometric-transform transforms the environment to a particular landmark object (in the example this is the box).

identify-location-proximal applies the spatial category given as argument to the input source set. The operation returns the single object which has the highest similarity with the spatial category. This operation applies proximal relations.

identify-location-projective works similar to the previous operation but is special to projective relations. We use the intrinsic notion of projective relations (Levinson, 2003). Landmarks such as the box and the robots can have an inherent orientation which highlights one of their sides as being the front.

identify-object-absolute encodes an absolute strategy. Absolute strategies compute rotation based on the direction towards a geocentric wall marker available in some spatial scenes.

Besides cognitive operations (algorithms), semantic structure also contains data. So called `bind`-statements introduce pointers to agent internal representations of concepts, prototypes and spatial relations. For example, `(bind proximal-category ?cat near)` introduces the spatial category `near`. Spatial relations are implemented using insights from cognitive semantics (Herskovits, 1986) and prototype theory (Rosch, 1975). There are two types of categories, distance-based (proximal) and angle-based (projective and absolute).

Angular relations Angular categories (projective and absolute relations) have a focal region around a specified axis. Similarity of some location to an angular category depends on the distance of angles. For instance, the front category has a high degree of applicability along the frontal axis. The following equations defines the degree of applicability, i.e. similarity, $\mathrm{sim}_a \in [0,1]$ given an object o and an angular category c and a parameter σ which steers the steepness of the function.

$$\begin{aligned} \mathrm{sim}_a(o,c) &:= e^{-\frac{1}{2\sigma_c}\,\mathrm{d}_a(o,c)} \\ \mathrm{d}_a(o,c) &:= |a_o - a_c| \end{aligned}$$

a_o denotes the angle of the position of o to the coordinate center and a_c is the prototypical angle of c.

Proximal relations Proximal relations are represented using prototypical distances.

$$\begin{aligned} \mathrm{sim}_d(o,c) &:= e^{-\frac{1}{2\sigma_c}\,\mathrm{d}_d(o,c)} \\ \mathrm{d}_d(o,c) &:= |d_o - d_c| \end{aligned}$$

d_o denotes the distance of the object o to the coordinate center and d_c is the prototypical distance of the proximal category c.

Spatial conceptualization strategies The IRL-program Figure 2 shows a specific semantic structure that is part of a specific conceptualization strategy, namely the proximal spatial strategy. If we remove the spatial relation from the IRL-program in that figure, we are left with a conceptualization strategy which involves a landmark (the box) and a (unspecified) proximal spatial relations. We call such partial structures *chunks* (Spranger et al., 2010). Chunks are reified conceptualization strategies. They have a score which represents how much the agent prefers the strategy over others (e.g., see Mainwaring et al., 2003 for preferences in perspective choice).

Spatial conceptualization strategies involve more than just a choice of spatial relations. Landmarks, perspective, frames of reference (Tenbrink, 2007) are all important aspects of the construal of spatial relations and researchers are still mapping out the taxonomies and unifying theories for the vast amount of spatial conceptualization strategies found in natural language (Levinson, 2003). For instance, which landmarks can be used with a particular spatial relation – just people, animals or also inanimate objects – is part of the choices manifest in a particular strategy. We can represent all these different factors using distinct cognitive operations and IRL-programs.

Production and interpretation When agents communicate they face the problem which language strategy to choose: proximal, projective or absolute. Within each strategy there is are additional choices which spatial relation the agent wants to use, and which landmark to emply. Finally, agents have to name the category and retrieve a name for it in order to make themselves understood[1]. Production – the process of finding an utterance for discriminating an object – and interpretation – the process of finding the topic given an utterance – are heuristics guided, automated search processes that try to find good semantic structure (IRL-programs).

Production In production, agents choose the spatial conceptualization strategy and the spatial relation which is most *discriminating* the topic T with respect to all other objects in the context. A strategy and the chosen category are discriminating if they maximize the similarity of the topic but minimize the similarity of all other objects (Herskovits, 1986). Once the category is chosen, agents will verbalize the category by retrieving the term associated with the category.

Interpretation In parsing, this process is reversed and agents use their lexicon to find the category linked to the spatial term in the utterance. The category is used to find back the conceptualization strategy which is in turn applied together with the spatial relation to single out the topic.

We use *Fluid Construction Grammar* (FCG) (Steels and De Beule, 2006) for verbalization. FCG is a formalism developed for language evolution in which linguistic knowledge is represented using form-meaning associations, so called *constructions*. Constructions are scored and can be freely and deleted from an agent's memory which allows to model the change of linguistic knowledge of that agent.

Constructions are not the only items that are scored. Production and interpretation are heavily influenced by the score of the different linguistic items. Spatial relations, conceptualization strategies (chunks) and lexical items all have individual scores associated with them which are used to weight the results. The scores reflect individual preferences.

[1]In this paper, agents are confined to uttering single words in spatial language games.

Co-Evolution of Spatial Relations

Conceptualization strategies are necessary prerequisites for building ontologies and lexicons. This section shows that given a chunk and a set of invention, adoption and alignment operators concrete systems of spatial relations can be negotiated in populations. Due to space constraints this section only exercises this for the projective strategy. Similar propositions hold for absolute and proximal strategies (Spranger, 2011b). The following paragraphs detail the operators.

Invention: *Speaker cannot find a discriminating spatial category in production*

- Diagnostic: When the speaker cannot conceptualize a meaning (step 2 of the spatial language game fails).
- Repair: The speaker constructs a spatial relation R based on the relevant strategy (projective) and the topic pointed at. The new category is necessary based on the distance or angle observed for the topic object (the initial sigma is small 0.1). Additionally, the speaker invents a new construction associating R with s.

Adoption: *Hearer encounters unknown spatial term s*

- Diagnostic: When the hearer does not know a term (step 3 fails).
- Repair: The hearer signals failure and the speaker points to the topic T. The hearer then constructs a spatial relation R based on the relevant strategy and the topic pointed at. Additionally, the speaker invents a new construction associating R with s.

Category alignment Projective categories are represented by prototypical angles. After each interaction agents update the prototypical angle to better reflect the new observation by averaging the angles of objects in the sample set S. The new prototypical angle a_c of the category is computed using the following formula for averaging angles.

$$a_c = \text{atan2}\left(\frac{1}{|S|}\sum_{s\in S}\sin a_s, \frac{1}{|S|}\sum_{s\in S}\cos a_s\right) \quad (1)$$

The new σ value σ' which describes the shape of the similarity function of the category is adapted using the following formula.

$$\sigma'_c = \sigma_c + \alpha_\sigma \cdot \left(\sigma_c - \sqrt{\frac{1}{|S|-1}\sum_{s\in S}(a_c - a_s)^2}\right) \quad (2)$$

This formula describes how much the new σ_c of the category c is pushed in the direction of the angle standard deviation of the sample set by a factor[2] of $\alpha_\sigma \in [0, \infty]$.

[2]α is given by the experimenter and in all experiments described here $\alpha = 0.5$

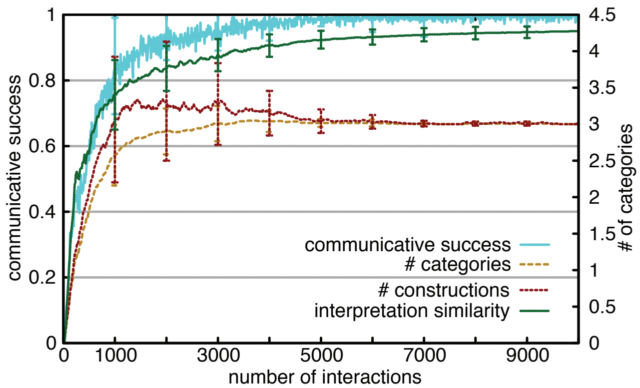

Figure 3: Results for a formation experiment in which agents develop a projective category system.

Lexicon alignment The invention and adoption repairs introduce a particular problem – the problem of *synonymy*. Synonymy occurs when an agent explicitly represents that a spatial category can be named using different spatial terms. Each of these different names is represented using a separate construction each of which links the synonymously used category to a different string. Allowing agents to track synonymy in their lexicons can be beneficial for overall lexicon size, but only if agents also have additional mechanisms for managing synonymy. Such a mechanism, called *lateral inhibition*, was introduced in Steels (1995):

- In case the interaction was a success both speaker and hearer reward the winning construction – the one used in production and interpretation – by a score of δ_{success}. Competing constructions are punished by δ_{inhibit}. There are two types of competing constructions. First, there are those constructions which associate the same spatial relation but with a different word. Second, there are constructions that link the same word to different spatial relations.

- After a failed game, both speaker and hearer decrease the score of the used association with δ_{fail}.

Measures To be sure that our approach to formation works reliably, we test it by running multiple trials of the same experiment. In each trial agents start with an empty ontology and lexicon. Success, performance and language development of the population are tracked using the following measures.

Communicative Success Communicative success is the most important measure as it reflects the overall performance of the population. Every interaction is either a success or a failure. Success is counted with 1.0 and failure is counted as 0.0.

Number of Categories and number of constructions This measure simply counts the average number of categories and constructions known to the agent.

Interpretation Similarity This is a measure tracking how similar the interpretation of each word known to each agent is. For this the categories attached to the word in each agent is compared. Since projective categories are described by a direction and a similarity function width parameter σ, two categories are most similar (1.0) when both angle and σ are equal.

Results Figure 3 shows the dynamics of experiments in which 10 agents start without any categories and constructions and gradually have to solve their communicative problems by invention and adoption of linguistic and semantic material (25 trials). In each trial 10000 spatial language games are played, with two agents randomly drawn from the population, interacting, and inventing, adopting and aligning linguistic knowledge.

The graph shows that agents are able to form successful language systems that gradually become more and more similar in the population as the linguistic knowledge spreads from agent to agent. After 10000 interactions agents are communicating successfully in over 95% of the interactions. In all trials, the population agrees on using a total of three spatial relations and corresponding names.

Selection and Alignment of Spatial Conceptualization Strategies

The previous section demonstrated that given a conceptualization strategy and strategies for invention, adoption and alignment agents can co-evolve successful systems for referring to objects in their environment. The important claim in this section is that conceptualization strategies are negotiated in a cultural process, similar to how the lexicon is negotiated, through local interactions by agents in a community. The idea is that a particular strategy survives when it is relevant to an agent because it is efficient and useful in discriminating objects and it contributes to the communicative success of an agent at least in a few spatial contexts.

Selection and Alignment Selection of a strategy is intricately linked to the success of the ontology and lexicon, i.e. spatial category system, it builds. For instance, if an agent is building a language system with an absolute strategy this entails that the absolute relations and the strategy itself are subject to the same selective pressure. It is the success of the overall system, i.e. the spatial relations together with the performance of the strategy, that drives the organization of the syntactic and semantic repository of the agent.

The previous section talked about the invention and alignment of words and categories. The same operators are used for building different language systems. Additionally, the

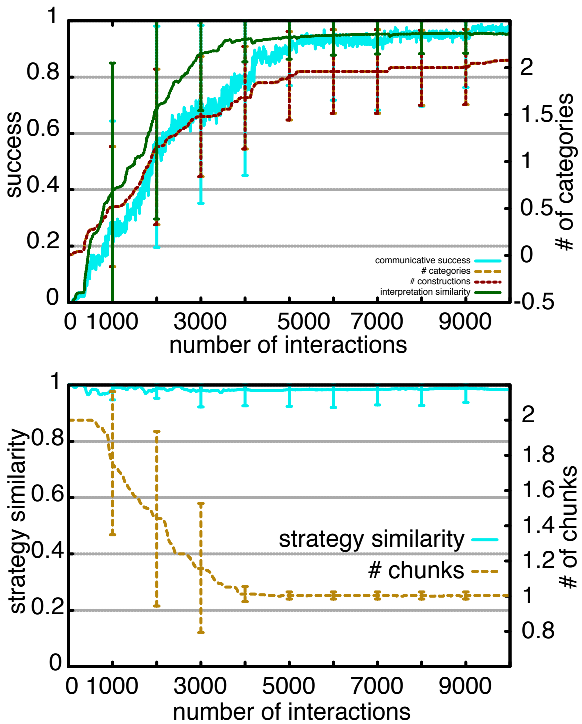

Figure 4: Dynamics of a category formation experiment in which 10 agents align the conceptualization strategy used at the same time.

success of a strategy, i.e. chunk, is tracked after every interaction by updating its score. If the conceptualization strategy was used successfully its score is increased by a factor δ_{success} otherwise it is punished by δ_{failure}. All other conceptualization strategies not used are punished by the score $\delta_{\text{competitor}}$. The value of these deltas is typically by a magnitude lower than the deltas for updating categories and words.

Measures We test our approach by running experiments in which agents are given different conceptualization strategies. To monitor the alignment of conceptualization strategies we use an additional measure.

Number of chunks This measure averages the number of conceptualization strategies with a score bigger than 0 over every agent.

Conceptualization strategy similarity The css is defined for a population P as the average acss for every two agents. Since acss is symmetric, all combinations of two agents are considered.

Agent conceptualization strategy similarity The acss is computed by comparing the score of each strategy. Since strategies are never removed but merely reduced to a score of 0.0 we can compute a distance of scores between the chunks in each agent and envelope the result using an exponential decay function which results in the following formula.

$$\mathrm{acss}(a_1, a_2, S) := e^{\left(-1\cdot\sum_{s\in S}|\,\mathrm{score}(s,a_1)-\mathrm{score}(s,a_2)|\right)}$$

In this formula a_1, a_2 are the agents whose similarity score is computed, S is the set of strategies given to agents and $\mathrm{score}(s, a_1)$ is the score agent a_1 gives to strategy s.

Experimental Setup and Results We test the power of strategy alignment using contexts which can be manipulated to feature absolute and intrinsic properties. More specifically, we manipulate the distribution of intrinsic and absolute properties in the environment. Figure 4 shows the dynamics of an experiment where agents start equipped with two strategies: an absolute and an intrinsic one. The environment is such that it favors absolute systems. In 50% of the scenes both intrinsic and absolute features are present. In the remaining 50% of the contexts only absolute features are present and no intrinsic ones.

The environmental conditions have a strong effect on the development of the system. All 25 populations agree on using an absolute strategy. What is important is that the contexts where only absolute features are present reward the absolute strategy and punish the intrinsic conceptualization strategy. Consequently, even in a context where intrinsic and absolute features are present, the absolute strategy is preferred. The development of such a preference has important effects on the invention of categories. Because of the preference for the absolute strategy, invention of categories shifts to producing only absolute categories. The successful use of these categories enforces the absolute strategy and leads to further punishment of the intrinsic strategy. The effect is that only the absolute strategy survives. Additionally, the graph shows that roughly together with the category system, agents align their conceptualization strategy.

Recruitment of Conceptualization Strategies

Conceptualization strategies are networks of cognitive operations encoding a particular way of construing reality. Consequently, they originate in a process of *recruitment* which assembles cognitive operations into strategies, i.e. chunks. Recruitment is a necessary pre-requisite for the usage of conceptualization strategies and their alignment in a population. Once a chunk is invented it immediately extends the conceptualization capabilities of the inventing agent.

Recruitment Strategy invention is deeply integrated into the processing of agents. Agents unable to conceptualize or unable to conceptualize with sufficient confidence diagnose a problem which is fixed by a repair that starts the search for new conceptualization strategies. The reason for this integration specifically with other invention mechanisms such as

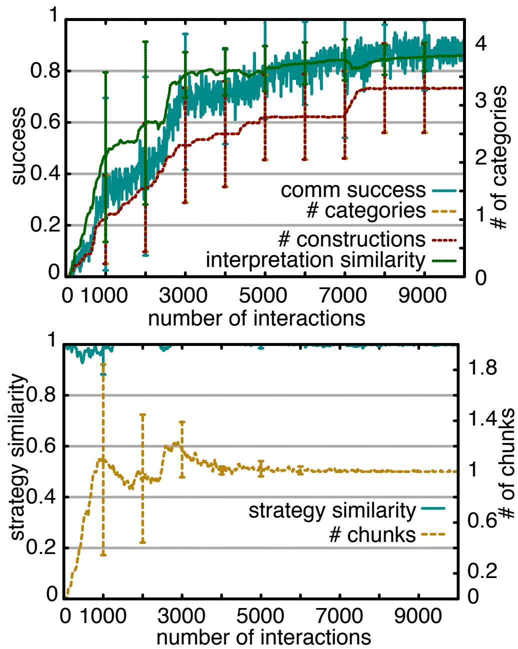

Figure 5: Results for strategy invention, alignment and category development. A population of 10 agents develops both conceptualization strategies as well as lexical systems for spatial strategies corresponding to these strategies.

category invention is that agents when inventing new strategies also immediately have to invent new categories with these strategies because a strategy itself is not verbalized but the name of the spatial relation. This sort of dual invention is especially important in the beginning of experiments, when agents have neither developed strategies nor categories.

But there is a second reason for deep integration of strategy invention. When an agent already has developed a strategy then he might also solve a particular communicative problem by inventing new categories for established strategies. Such decisions whether to use a new category with an existing strategy or a new strategy with an existing category, or even to use a newly invented strategy with a newly invented category are made based on the discriminative power of each these different possibilities in the particular context. So for instance if an existing strategy has a low score the probability of inventing a new strategy increases, whereas if the current topic can be sufficiently discriminated using an existing strategy no invention occurs.

We need two more operators besides the operators discussed in previous sections.

Invention: *Speaker cannot find a meaning for referring to the topic*

- Diagnostic: When the speaker cannot conceptualize a meaning (step 2 of the spatial language game fails).
- Repair: The speaker invents new conceptualization strategies by assembling cognitive operations such as `identify-proximal`, `geometric-transform` into chunks which is immediately followed by the invention of categories for each new chunk (see section on co-evolution of categories and terms). At this point the speaker might have a number of new solutions to his conceptualization problem consisting of new strategies and new corresponding spatial relations. Subsequently, the speaker selects the strategy and category which is *most discriminating*. Once selected, he invents a new word and construction for expressing the new strategy.

Adoption: *Hearer encounters unknown spatial term s*

- Diagnostic: When the hearer does not know a term (step 3 fails).
- Repair: The hearer signals failure and the speaker points to the topic T. The hearer then constructs new strategies, i.e. chunks, and for each of them he invents a new spatial relation R_i based on the the topic pointed at. The hearer then decides on which of the strategies is most discriminating. This is the one selected for storing. Additionally, the hearer invents a new construction linking R_i with s.

These two invention and alignment operators are specific to the invention of chunks. Moreover, agents are equipped with the selection and alignment operators for chunks, spatial relations and words discussed earlier.

Results Figure 5 shows the dynamics of invention and alignment of conceptualization strategies in a population of 10 agents (25 trials). Agents have a repository of 10 basic cognitive operations from which they can draw new building blocks whenever there are problems in communication. They can choose different landmarks: the robot, or the box, and different category systems absolute and intrinsic projective, as well as proximal. The agents manage to agree on one particular strategy while at the same time developing a category system and a lexicon from scratch.

However, the process does not show the same overall success as previously discussed experiments. The reason is that conceptual alignment is a difficult process which is complicated by the number of choices in strategies, population size and the variety of different contexts and discriminative situations which might all favor different strategies. In some contexts proximal is the best strategy, some allow absolute and/or projective categories to be invented. Nevertheless, agents do come to an agreement. Here, they agree on average on a single conceptualization strategy.

For space reasons, we can only discuss one particular experiment with trials all equal in environmental condition. But, of course once the system is setup one can study the effect of varying conditions. The systems discussed here are very flexible and find solutions to different environmental conditions featuring additional landmarks, intrinsic and absolute features. Additionally, agents react flexibly to different object distributions that favor distance-based or angle-based strategies.

Discussion

This papers has argued for selection, recruitment and alignment as the basic mechanisms explaining the evolution of language strategies together with corresponding language systems. We have shown (1) how strategies can be be represented, (2) how strategies build language systems, (3) how selection works on strategies and (4) how strategies are build by recruiting cognitive operations. We provided mechanistic explanations and validated them in robotic experiments.

The basic claim validated is that we can understand the evolution of strategies as a process of cultural negotiation fueled by the cognitive capabilities of agents, i.e. the cognitive operations available. The process is constrained by environmental factors such as the availability of geocentric landmarks. While cognition and ecology influence the selection process, the negotiation takes place within a single static population via linguistic interactions. This is also the main difference to other models of cultural evolution which claim that intergenerational turnover is the main cause of language change (Kirby, 2002; Smith et al., 2003).

We have only considered a simple lexical verbalization strategy. Certainly, spatial language shows much more variation in the kinds of syntactic material that is employed to convey distinct spatial semantics. A discussion can be found in Levinson and Wilkins (2006) and Tenbrink (2007) and evolutionary models in Spranger (2011a). Moreover, spatial language can feature other conceptualization strategies involving toponyms, directional categories or body-centered spatial relations. Given a suitable implementation of cognitive operations, we claim that the same approach can be used to study the evolution of such strategies.

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References

Beckner, C., Blythe, R., Bybee, J., Christiansen, M. H., Croft, W., Ellis, N. C., Holland, J., Ke, J., Larsen-Freeman, D., and Schoenemann, T. (2009). Language is a complex adaptive system: Position paper. *Language Learning*, 59:1–26.

Bleys, J. (2010). *Language Strategies for the Domain of Colour*. PhD thesis, Vrije Universiteit Brussels (VUB), Brussels, Belgium.

Fujita, M., Kuroki, Y., Ishida, T., and Doi, T. (2003). Autonomous behavior control architecture of entertainment humanoid robot SDR-4X. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 960–967.

Herskovits, A. (1986). *Language and spatial cognition*. Studies in Natural Language Processing. Cambridge University Press.

Johnson-Laird, P. N. (1977). Procedural semantics. *Cognition*, 5(3):189–214.

Kemmerer, D. (1999). "Near" and "far" in language and perception. *Cognition*, 73(1):35 – 63.

Kirby, S. (2002). The evolution of language. *Artificial Life*, 8:185–215.

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

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

Mainwaring, S., Tversky, B., Ohgishi, M., and Schiano, D. (2003). Descriptions of simple spatial scenes in English and Japanese. *Spatial Cognition and Computation*, 3(1):3–42.

Rosch, E. (1975). Cognitive representations of semantic categories. *Journal of Experimental Psychology: General*, 140:192–233.

Smith, K., Kirby, S., and Brighton, H. (2003). Iterated learning: A framework for the emergence of language. *Artificial Life*, 9(4):371–386.

Spranger, M. (2008). World models for grounded language games. German diplom thesis, Humboldt-Universität zu Berlin.

Spranger, M. (2011a). A Basic Emergent Grammar for Space. In Steels, L., editor, *Experiments in Cultural Language Evolution*. John Benjamins, Amsterdam.

Spranger, M. (2011b). The Co-Evolution of Basic Spatial Terms and Categories. In Steels, L., editor, *Experiments in Cultural Language Evolution*. John Benjamins, Amsterdam.

Spranger, M., Loetzsch, M., and Pauw, S. (2010). Open-ended grounded semantics. In *Proceedings of the 19th European Conference on Artificial Intelligence (ECAI 2010)*, pages 929–934. IOS Press.

Steels, L. (1995). A self-organizing spatial vocabulary. *Artificial Life*, 2(3):319–332.

Steels, L. (2007). The Recruitment Theory of Language Origins. In *The Emergence of Communication and Language*, pages 129–151. Springer.

Steels, L. (2011). Self-organization and Selection in Cultural Language Evolution. In Steels, L., editor, *Experiments in Cultural Language Evolution*. John Benjamins.

Steels, L. and De Beule, J. (2006). Unify and merge in Fluid Construction Grammar. In *Symbol Grounding and Beyond: Proceedings of EELC*, LNAI (4211), pages 197–223. Springer.

Tenbrink, T. (2007). *Space, time, and the use of language: An investigation of relationships*. Walter de Gruyter.

van Trijp, R. (2010). Strategy competition in the evolution of pronouns: A case-study of Spanish leísmo, laísmo and loísmo. In *The Evolution of Language (EVOLANG 8)*, pages 336–343. World Scientific.