A self-organizing spatial vocabulary.

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Abstract

Language is a shared set of conventions for mapping meanings to expressions. This paper explores self-organization as the primary mechanism for the formation of a vocabulary. It reports on a computational experiment in which a group of distributed agents develop ways to identify each other using names or spatial descriptions. It is also shown that the proposed mechanism copes with the acquisition of an existing vocabulary by new agents entering the community and with the expansion of the set of meanings.

1 Introduction

How did language originate and how are agents capable to acquire the existing language of their community? Various theories have been offered in the linguistic and cognitive science literature. One theory, proposed and defended by Chomsky and his school, states that grammar is innate [1]. More precisely, there is an innate language acquisition device based on a universal grammar so that the acquisition of a new language is a matter of setting switches (choosing parameters). If universal grammar is innate, then presumably language arises and develops as a consequence of genetic mutations. Such a hypothesis has indeed been put forward and is investigated by linguists and biologists alike [8].

In a series of experiments, I am exploring a different approach which is summarised in the following two hypotheses:

[1] Language is an autonomous adaptive system which forms itself in a self-organizing process. Language is therefore similar to other self-organizing phenomena observed in biosystems, such as paths in an ant society, clouds of birds, etc. [5]. A language is viewed as an adaptive system in the sense that it has to allow its users to express an open-ended, ever growing or changing set of meanings with an open-ended but finite set of building blocks and combinations of building blocks. The speakers and hearers are distributed agents that through their localised linguistic behavior (namely the carrying out of conversations) shape and reshape the language. No agent has a complete view of the language and no agent can control the linguistic behavior of the whole group. Moreover no separate mechanism for language acquisition is necessary because the mechanisms that explain the formation of language also explain how it is acquired by new agents entering the community.

[2] Language spontaneously becomes more complex. The development and evolution of language towards greater complexity is primarily driven by the need to optimize communicative success and handle the very strong constraints which hold for open-ended real world languages, namely limited time to communicate, limited time to process the utterance, weak and error-prone acoustic transmission, limited feedback about success, constraints of the vocal apparatus, etc.

This paper reports on one specific experiment to concretise and test the first hypothesis. It applies a mechanism proposed and investigated abstractly in an earlier paper [9] to a concrete domain, namely spatial terms. The experimental challenge consists in showing that a distributed set of agents can develop from scratch a vocabulary to identify each other through names and spatial descriptions. This research is complementary to related 'alife' experiments that have investigated the origin of communication [3], the origin of vocabulary [6], and the growth in complexity of syntax [7]. The emphasis in the present work is on self-organization as opposed to genetic evolution for the creation and maintenance of complexity.

The rest of the paper is in 4 parts. The next section introduces the conceptual framework shared by the agents and hence the possible meanings.

Section 3 describes the nature of dialogs and conversations. Section 4 explains the language formation process based on self-organization. Section 5 focuses on the problem of language acquisition and meaning expansion.

2 Spatial concepts

Assume a set of agents: $\{a_1, ..., a_n\}$. The agents are located in a 2-dimensional grid. The x and y coordinates of an agent a are denoted as x_a and y_a. Each agent has also a specific orientation: north, east, south, west. For the purposes of this paper all agents are assumed to point north.

The agents are assumed to have a perceptual apparatus that operates on their visual field so that they can perceive elementary spatial relationships between themselves and other agents. Perception can be used for two purposes: (1) An agent can determine in which direction an object is located and use that to identify this object for another agent, (2) An agent can determine which objects satisfy a given spatial description and can use that to identify which object another agent is referring to. Agents share the same context when they engage in a conversation. Thus the spatial relationships are perceivable by both of them, although they are viewpoint depended. This paper does not discuss how these perceptions have become meaningful but only how a vocabulary develops to express them.

The following spatial relationships have been defined. They are all relative to the agent's coordinate system although they are defined here in the absolute x-y coordinate system assuming the agent is pointing north:

- **Front**: This relation is valid if the object p is located in front of the agent a. $y_p > y_a$.
- **Side**: This relation is valid if the object is located on the same axis as the agent (left or right) $y_p = y_a$.
- **Behind**: This relation is valid if the object is located behind the agent. $y_p < y_a$.
- **Left**: This relation is valid if the object is to the left side of the agent, i.e. $x_p < x_a$.

- **Straight**: This relation is valid if the object is right in front or right behind the agent, i.e. $x_p = x_a$.
- **Right**: This relation is valid if the object is to the right side of the agent, i.e. $x_p > x_a$.

When other orientations are also taken into account, the numerical definitions of a relation defined in the absolute coordinate system are different. For example, front is defined as $y_p < y_a$ if the agent is oriented to the south. But viewed from the relative coordinate system of the agent the relation is the same. The problem to be considered in this paper is how agents can develop autonomously and in a distributed fashion a vocabulary to express these perceptual categories and use them to identify objects.

3 Dialogs as language-games

Linguistic behavior can be viewed as a series of *language-games*, as already pointed out by Wittgenstein [10]. In each game a number of participants (at least a speaker and hearer) come together in a shared context. The game has many dimensions: There is a communicative dimension, for example the speaker wants to draw attention to a particular object. There is a linguistic dimension because speaker and hearer negotiate about which expressions should be part of their language. There is a social dimension which may, for example, imply and thus re-enforce specific hierarchical relations between speaker and hearer. The social dimension will not be explored in this paper. Language-games are a special case of interactions between agents and may also include non-linguistic modes of interaction such as pointing.

A *conversation* is a particular language-game. A series of conversations is called a *dialog*. There are many different types of conversations and dialogs. This paper focuses only on one type of dialog: where one agent refers to an object (which is here another agent) and the other agent tries to identify this object. The agent starting the dialog, further called the *initiator*, can choose which object the dialog is about. The other agent, further called the *receiver*, has to identify the object using linguistic means. The dialog continues until both agents reach a consensus about which object is intended or until they terminate the conversation because no such consensus could be reached or the required common vocabulary is missing. Conversations may either be based on names of agents or on spatial descriptions.

These various possible conversation types and dialogs are now illustrated, assuming that the following coherent shared language already developed among the agents:

meaning	word	meaning	word
RIGHT	(S U)	a-4	(J O)
SIDE	(G A)	a-1	(F I)
LEFT	(G E)	a-2	(L A)
FRONT	(Z E)	a-5	(T E)
STRAIGHT	(F U)		
BEHIND	(B A)		

3.1 Main dialog structure

A dialog has the following structure:

- *Initiation*: The initiator introduces the object in an extra-linguistic way, for example by pointing to it.
- *Communication*: The initiator uses language to identify the object.
- *Reply*: The receiver uses language to identify the object that he interprets the initiator to refer to.
- *Confirmation*: The initiator gives a final indication of whether the receiver got it right.

When there is already a sufficiently shared language, the first part (initiation) may be absent. In that case only linguistic means can be used to identify the object.

A conversation in which an *expression* to denote a *meaning* is communicated from a *speaker* to a *receiver* is printed out as:

```
=> speaker: list-of-meanings
   speaker: meaning -> expression <- receiver: meaning
```

The *list-of-meanings* is the list of meanings that the speaker wants to express. If there is more than one the first meaning is taken.

Here is an example of a dialog taking place between two agents a-3 (the initiator) and a-4 (the receiver). The object is a-5. a-3 first points to the object and then uses the name (T E). a-4 replies by using the same name. a-3 confirms that this is indeed the object.

```
Dialog 11 with a-3 a-4
 => a-3: (a-5)
   a-3: a-5 -> 'point at a-5' <- a-4: a-5
   a-3: a-5  -> (T E)  <- a-4: a-5
 => a-4: (a-5)
   a-4: a-5  -> (T E)  <- a-3: a-5
 => a-3: (a-5)
   a-3: confirm -> 'yes' <- confirm
```

Next an example with the same dialog structure but now a spatial description is used by the initiator a-2. The initiator uses himself as the viewpoint of the description. He first identifies himself using the word (F A), and then communicates that the object of interest (which happens to be a-4 itself) is to the left front of a-2 using the words (Z E) (G E). a-4 identifies this as referring to a-4. (the only object satisfying this description) and replies by using its name for a-4, namely (J O). This is confirmed as being the right object by a-2.

```
Dialog 12 with a-2 a-4
 => a-2: (a-4)
   a-2: a-4 -> 'point at a-4' <- a-4: a-4
   a-2: a-2  -> (F A)  <- a-4: a-2
   a-2: FRONT  -> (Z E)  <- a-4: FRONT
   a-2: LEFT  -> (G E)  <- a-4: LEFT
 => a-4: (a-4)
   a-4: a-4  -> (J O)  <- a-2: a-4
 => a-2: (a-4)
   a-2: confirm -> 'yes' <- a-4: confirm
```

Here is third example, but now without prior initiation. The dialog is started with a spatial description given by a-3 to identify a-2. The other agent a-4 replies also with a spatial description. Both uniquely identify the object.

```
Dialog 50 with a-3 a-4
 => a-3: (a-2)
   a-3: a-3  -> (L A)  <- a-4: a-3
   a-3: SIDE  -> (G A)  <- a-4: SIDE
   a-3: LEFT  -> (G E)  <- a-4: LEFT
 => a-4: (a-2)
   a-4: a-4  -> (J O)  <- a-3: a-4
   a-4: BEHIND  -> (B A)  <- a-3: BEHIND
   a-4: RIGHT  -> (S U)  <- a-3: RIGHT
 => a-3: (a-2)
   a-3: confirm -> 'yes' <- a-4: confirm
```

3.2 Dialog with iteration

It may happen that the spatial description does not identify uniquely one single object. In that case an iteration starts where the participants take turns in order to shrink down the set of possible meanings. Here is such an example. a-4 identifies a-2 to a-5 by specifying that it is behind a-4 to the right, or in agentspeak: (J O)(B A)(S U). However there are 4 objects in that position: a-5, a-1, a-2, and a-3. a-5 first asks whether the object is straight to its side (T E)(G A)(F U). The answer is 'no' which eliminates a-5 from the list of possibilities. Then a-5 asks whether it is in front to the right (T E)(Z E)(S U). The answer is again 'no', which eliminates a-1 and a-3. Only a-2 remains. a-5 asks for a confirmation using the name (F A). And now the response is positive.

```
Dialog 47 with a-4 a-5
 => a-4: (a-2)
   a-4: a-4  -> (J O)  <- a-5: a-4
   a-4: BEHIND  -> (B A)  <- a-5: BEHIND
   a-4: RIGHT  -> (S U)  <- a-5: RIGHT
 => a-5: (a-5 a-1 a-2 a-3)
   a-5: a-5  -> (T E)  <- a-4: a-5
   a-5: SIDE  -> (G A)  <- a-4: SIDE
   a-5: STRAIGHT  -> (F U)  <- a-4: STRAIGHT
 => a-4: (a-5)
   a-4: disconfirm -> 'no' <- a-5: disconfirm
```

```
=> a-5: (a-1 a-2 a-3)
  a-5: a-5  -> (T E)  <- a-4: a-5
  a-5: FRONT  -> (Z E)  <- a-4: FRONT
  a-5: RIGHT  -> (S U)  <- a-4: RIGHT
=> a-4: (a-1 a-3)
  a-4: disconfirm -> 'no' <- a-5: disconfirm
=> a-5: (a-2)
  a-5: a-2  -> (F A)  <- a-4: a-2
=> a-4: (a-2)
  a-4: confirm -> 'yes' <- a-5: confirm
```

4 Vocabulary formation

We now focus on how such a vocabulary may emerge spontaneously through a self-organizing process. Self-organization is a common phenomenon in certain types of complex dynamical systems. A complex dynamical system is a system where there are many elements that exhibit a dynamic behavior without a central control source. To support self-organization such a system must exhibit a series of spontaneous fluctuations and a feedback process that enforces a particular fluctuation so that it eventually forms a (dissipative) structure [4]. The feedback process is related to a particular condition in the environment, for example an influx of materials that keeps the system in a non-equilibrium state. As long as the condition is present, the dissipative structure will be maintained. Some standard examples of self-organization are the Bhelouzow-Zhabotinsky reaction, morphogenetic processes, or the formation of a path in an ant society or a termite nest [2].

A vocabulary will be viewed as a dissipative structure similar to a path in an ant society. Each agent is assumed to create and continuously change his own vocabulary in a random fashion, resulting in a fluctuating linguistic community. Vocabularies must be shared in order to obtain the benefit of cooperating through communication. Hence the changes are coupled to communicative success: the higher the success the less probable a change. This results in a feedback process. When more agents use the same word for the same meaning, communicative success increases and therefore the word-meaning association becomes more stable. It has been shown in an earlier paper that coherence emerges (see figure 1) [9].

Figure 1: The results of a typical experiment with 10 agents, 5 possible words, and 1 meaning. It plots the communicative success of each word (y-axis) over time (x-axis). We see a search period in which different words compete until one gains complete dominance.

In the following subsections the mechanism is defined more formally and a concrete example of language formation is given.

4.1 The self-organizing kernel

A conversation involves two participants: a speaker s and a hearer h with language L_s and L_h and meaning sets M_s and M_h. The meaning that the speaker communicates is denoted as m_s. There are two possibilities. In the first case the hearer has already anticipated a meaning, denoted as m_h. In the second case the hearer has to pick up the meaning from the conversation. The meaning identified by the hearer at the end of the conversation is denoted as m_c. The communicative success of a conversation k is denoted as c_k. The self-organizing mechanism involves two steps: (1) determine communicative success, (2) change a word-meaning pair. As a side effect the propagation of meanings or the creation of new words may happen.

Determine communicative success

1. The speaker is not acquainted with the meaning: $m_s \notin M_s$. In this case m_s is added to M_s and $c_k = 0$. If the hearer is not acquainted with the anticipated meaning $m_h \notin M_h$, then m_h is added to M_h. $c_k = 0$

2. The speaker has a word w_s for m_s: $m_s \in M_s$ and $m_s \rightarrow w_s \in L_s$.

    2.1. The hearer has an association $m_c \rightarrow w_s \in L_h$.

    2.1.1. If the hearer had no anticipated meaning, it is assumed that the communication is successful $c_k = 1.0$.

    2.1.2. If the hearer has an anticipated meaning m_h but a different one, $m_c \neq m_h$. There are two possibilities: Either the hearer wrongly anticipated this meaning, and so the problem is outside the linguistic realm, or the hearer associates the wrong meaning with w_s. Because it is impossible to know, it is assumed that such a conversation has no further impact on the existing vocabulary. $m_c = m_h$.

    2.1.3. The hearer has an anticipated meaning which is the same, $m_c = m_h$. The conversation is a complete success: $c_k = 1.0$,

    2.2. The hearer has no association for this word. $c_k = 0.0$.

    2.2.1. If the hearer has anticipated a meaning, a coupling is constructed between w_s and m_h in L_h, but only if w_s is not yet used by h for something else and if m_h has no associated word in L_h. $m_c = m_h$.

    2.2.2. The hearer has no meaning anticipated. Nothing can be done further.

3. The speaker has no word for m_s and consequently nothing is said in the conversation.

The communicative success is recorded for m conversations (in later experiments m= 5) in which a particular association between a word and a meaning is used before any changes are considered. When a change is considered the average communicative success is calculated and used. The context of the last conversation (in particular the words used) influence the change.

Changing a word-meaning pair.

Changes in the coupling between w and m should depend on average communicative success of that coupling. When the same coupling had an average of 1.0, i.e. $c_{w,m} = 1.0$, there should obviously be no changes. When $c_{w,m} = 0.0$, there should obviously be changes. Intermediate decisions are based on a sigmoid function:

$$\frac{1}{1 + e^{-4tan\beta(x-a)}} \tag{1}$$

with $a = 0.49$ and $\beta = 80^o$ so that the probability of change decreases quickly as more than a majority adopts the same coupling.

A change in a coupling can take two forms:

- 1 No word was used in the last conversation. This would be the case if no word-meaning pair exists yet. In that case, a new word is created with a certain probability (in this paper 0.05).

- 2 A word was used in the last conversation. This word is then probabilistically adopted in the new word-meaning coupling.

A series of dialogs (possibly in parallel) take place between the agents. For each dialog, an initiator and a receiver are selected randomly from the total population. An object is selected randomly. A random choice determines whether a dialog is with or without prior initiation and whether an object will be referred to using a name or a spatial description. In each conversation the two processes (determine communicative success and change word-meaning pair) take place and the vocabulary self-organizes as a side effect of the dialogs as illustrated in the next subsection.

4.2 Examples

Consider a set of agents a-16, a-17, a-18, a-19, a20 distributed as in the following figure:

```
----- ----- ----- ----- a-24 ----- ----- ----- ----- a-23
----- ----- ----- a-21 ----- ----- ----- ----- ----- -----
----- ----- ----- ----- ----- ----- ----- ----- ----- -----
```

```
----- ----- ----- ----- ----- ----- ----- ----- ----- -----
----- ----- ----- ----- ----- ----- ----- ----- ----- -----
----- ----- ----- ----- ----- ----- ----- ----- ----- -----
----- ----- ----- ----- ----- ----- ----- ----- ----- -----
----- ----- ----- ----- ----- ----- ----- ----- ----- -----
----- ----- ----- a-25 ----- ----- ----- ----- ----- -----
----- ----- ----- ----- a-22 ----- ----- ----- ----- -----
```

The agents start without any vocabulary at all. The choice of dialog type or conversation type is made randomly, although certain conversations (for example those using spatial descriptions) will not be possible unless the agents have already a partially shared vocabulary of names for each other. We look at four snapshots of the language formation process. Initially most conversations fail but meanings propagate. In the last conversation a first word is created

```
Dialog 18 with a-24 a-22 ; dialog without prior initiation
 => a-24: (a-23)
   a-24: a-23 adopted      ; meaning propagates
 => a-22: NIL              ; the dialog fails
...
Dialog 20 with a-22 a-23 ; dialog with prior initiation
 => a-22: (a-23)
   a-22: a-23 -> 'point at a-23' <- a-23: a-23
   a-22: a-23 adopted
 => a-23: NIL              ; the dialog fails
...
Dialog 27 with a-24 a-22 ; dialog with prior initiation
 => a-24: (a-24)           ; meaning is known but no word yet
   a-24: a-24  -> ?  <- a-22: ?
 => a-22: NIL
...
Dialog 30 with a-21 a-24
 => a-21: (a-25)
   a-21: a-25  -> ?  <- a-24: ?
     !! a-21: a-25 -> (M I)   ; first word is created
 => a-24: NIL
```

After 200 conversations, the vocabulary looks as follows. The different meanings are listed followed by the words used and the agents which use each word behind square brackets. nil means that no word has been chosen yet.

```
RIGHT: nil:[a-25]
FRONT: (Z I):[a-25]
STRAIGHT: nil:[a-25, a-22]
SIDE: nil:[a-25, a-22]
a-23: (B A):[a-25, a-21] (G U):[a-24] (N E):[a-23] (L I):[a-22]
a-21: nil:[a-25, a-24, a-23, a-22, a-21]
a-22: nil:[a-25, a-22] (G A):[a-24, a-23, a-21]
a-25: (B I):[a-25, a-22] (L E):[a-24] (J U):[a-23] (M I):[a-21]
a-24: (X I):[a-25, a-23] (B O):[a-24] (F A):[a-22] (M A):[a-21]
```

We can see that there is hardly any consensus about which word to use. Only for (G A), used to refer to a-22, is there the beginning of some clustering with 3 agents [a-24, a-23, a-21] using it. When the dialogs continue we see already some conversations which are successful. No spatial vocabulary has been developed yet.

```
Dialog 218 with a-24 a-23
 => a-24: (a-25)
   a-24: a-24  -> (B O)  <- a-23: ?
 => a-23: NIL          unsuccessful although initiator has word
...
Dialog 230 with a-23 a-24
 => a-23: (a-22)
   a-23: a-22  -> (G A)  <- a-24: a-22
 => a-24: (a-22)
   a-24: a-22  -> (G A)  <- a-23: a-22
 => a-23: (a-22)      ; first successful conversation
   a-23: confirm -> 'yes' <- a-24: confirm
...
Dialog 242 with a-25 a-22
 => a-25: (a-23)      ; first attempt to use spatial descriptions
   a-25: a-25  -> (B I)  <- a-22: a-25
   a-25: FRONT  -> (Z I)  <- a-22: ?
   a-25: RIGHT  -> ?  <- a-22: ?
```

```
 => a-22: NIL
```

After 300 more conversations, the vocabulary looks as follows. Much more coherence has been reached and spatial meanings are propagating further in the population. Some words already exist for certain spatial relations (front, straight and side). There is a complete consensus to name a-21 (T I).

```
BEHIND = nil:[a-21]
LEFT = nil:[a-22]
RIGHT = nil:[a-25, a-23, a-22, a-21]
FRONT: nil:[a-24] (Z I):[a-25] (X O):[a-23, a-22, a-21]
STRAIGHT: (R U):[a-25] (J A):[a-24, a-23, a-22, a-21]
SIDE: nil:[a-25, a-24, a-23, a-22] (K U):[a-21]
a-23: nil:[a-22] (B A):[a-25, a-24, a-21] (P I):[a-23]
a-21: (T I):[a-25, a-24, a-23, a-22, a-21]
a-22: nil:[a-25] (G A):[a-24, a-23, a-22, a-21]
a-25: nil:[a-25, a-24] (B U):[a-23] (B I):[a-22] (L E):[a-21]
a-24: nil: a-24 (X I):[a-25, a-23, a-21] (F A):[a-22]
```

Dialogs involving spatial descriptions are now beginning to take place. Dialogs based on naming are almost always successful.

```
Dialog 518 with a-21 a-22
 => a-21: (a-24)
   a-21: a-24 -> ‘point at a-24’ <- a-22: a-24
   a-21: a-21  -> (T I)  <- a-22: a-21
   a-21: FRONT  -> (X O)  <- a-22: FRONT
   a-21: RIGHT  -> ?  <- a-22: ?
     !! a-21: RIGHT -> (X E)  ; new word for right in a-21
 => a-22: NIL
...
Dialog 522 with a-24 a-25
 => a-24: (a-21)
   a-24: a-21 -> ‘point at a-21’ <- a-25: a-21
   a-24: a-21  -> (T I)  <- a-25: a-21
 => a-25: (a-21)
   a-25: a-21  -> (T I)  <- a-24: a-21
 => a-24: (a-21)
   a-24: confirm -> ‘yes’ <- confirm
```

After 500 more conversations, the vocabulary is almost completely established:

```
BEHIND: (T U):[a-25, a-24, a-23, a-22, a-21]
LEFT: nil:[a-22] (L O):[a-25, a-24,a-23, a-21]
RIGHT: (X E):[a-25, a-24, a-23, a-22, a-21]
FRONT: (X O):[a-25, a-24, a-23, a-22, a-21]
STRAIGHT: (J A):[a-25, a-24, a-23, a-22, a-21]
SIDE: (V A):[a-25, a-23, a-22] (K U):[a-24, a-21]
a-23: (B A):[a-25, a-24, a-23, a-22, a-21]
a-21: (T I):[a-25, a-24, a-23, a-22, a-21]
a-22: (G A):[a-25, a-24, a-23, a-22, a-21]
a-25: (B U):[a-25, a-24, a-23] (B I):[a-22,a-21]
a-24: (X I):[a-25, a-24, a-23, a-22, a-21]
```

There are now long dialogs with full use of spatial descriptions. Here is an example dialog where the object is introduced by a-25 using a spatial description and confirmed by a-23 using another spatial description:

```
Dialog 1142 with a-25 a-23
 => a-25: (a-25)
   a-25: a-25  -> (B U)  <- a-23: a-25
   a-25: SIDE  -> (V A)  <- a-23: SIDE
   a-25: STRAIGHT  -> (J A)  <- a-23: STRAIGHT
 => a-23: (a-25)
   a-23: a-23  -> (B A)  <- a-25: a-23
   a-23: BEHIND  -> (T U)  <- a-25: BEHIND
   a-23: LEFT  -> (L O)  <- a-25: LEFT
 => a-25: (a-25)
   a-25: confirm -> 'yes' <- confirm
```

Figure 2 and 3 give an overview of the language formation process. We see that after an initial phase of confusion, most of the language gets established after about 1000 conversations. Sometimes it takes more time before complete coherence is reached (for the last meaning it took here 3000 conversations. This is partly due to the fact that the relevant meanings and words must come up in a conversation. Figure 3. shows that communicative success reaches 80 % and higher after about 1000 conversations.

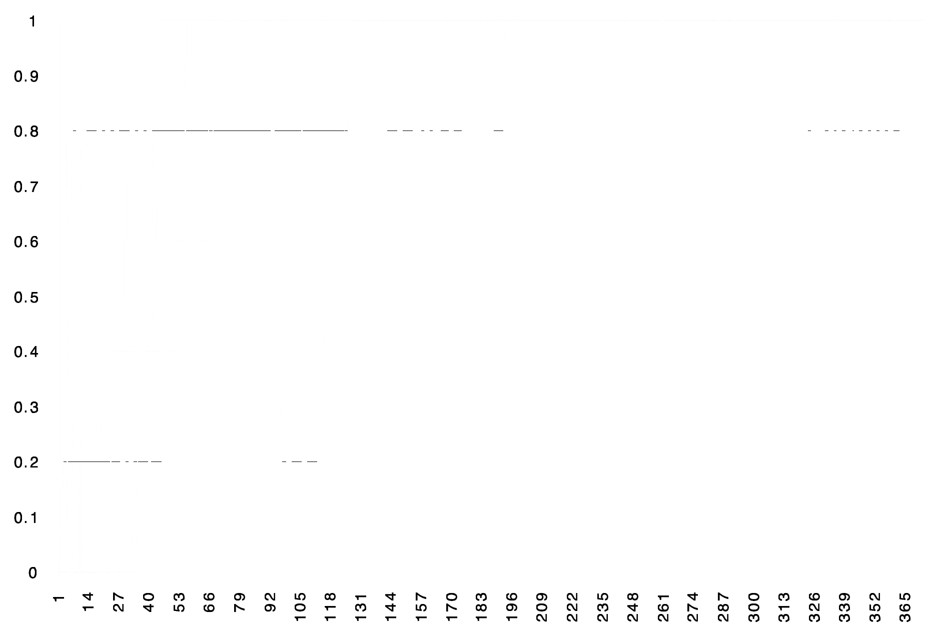

Figure 2: This figure gives an overview of the vocabulary formation process. The x-axis represents the number of conversations (scale 1:10). The y-axis represents the percentage of agents using the same word for the same meaning.

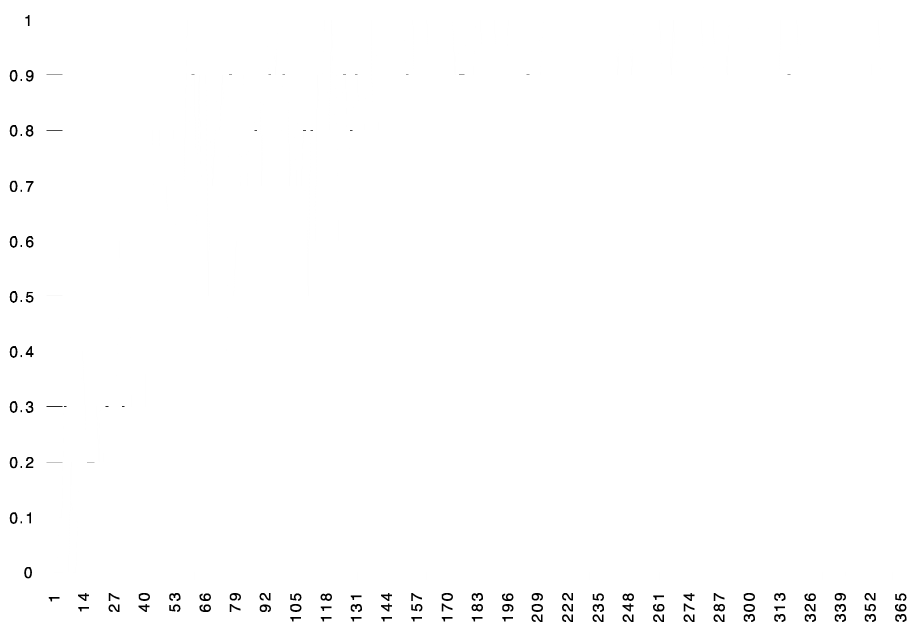

Figure 3: This figure plots the communicative success for the same process as fig. 2. The x-axis represents the number of conversations (per tens). The y-axis the communicative success.

4.3 Language acquisition

The characteristic feature of a true natural language is that it is open. It keeps evolving in order to adapt to new meanings that arise in the community, influences from neighboring languages, and communicative pressures. It also absorbs new members in the community and other members disappear without destabilising the language. New members acquire the existing language in the community. In this section, it is shown that the same mechanism that gives rise to the vocabulary also explains that new meanings or new agents enter into the population. New meanings will come up and propagate in the population as before, and new words will be created if needed. New members start by adopting words in specific conversations or they may temporarily create their own. Because there is already a well-entrenched language, the new words or couplings created will not survive because they do not achieve any communicative success and the agent will progressively adopt the language of the group.

This is illustrated with the following experiment. A new agent a-26 is added to the existing set of agents. The new agent has no vocabulary and no name exists yet. Because each agent is also a potential meaning for the others, this experiment demonstrates at the same time that the vocabulary is automatically extended when the set of meanings expands. After 300 conversations, the new agent has adopted most of the common vocabulary although he uses (temporarily) a new word (J O) for a-21. The other agents are beginning to use the word (R E) to refer to the new agent.

```
a-26: nil:[a-24, a-23, a-21] (R E):[a-25, a-26, a-22]
BEHIND: (T U):[a-26, a-25, a-24, a-23, a-22, a-21]
LEFT: (L O):[a-26, a-25, a-24, a-23, a-22, a-21]
RIGHT: (X E):[a-26, a-25, a-24, a-23, a-22, a-21]
FRONT: (X O):[a-26, a-25, a-24, a-23, a-22, a-21]
STRAIGHT: (J A):[a-26, a-25, a-24, a-23, a-22, a-21]
SIDE: nil:[a-26] (V A):[a-25, a-24, a-23, a-22, a-21]
a-23: (B A):[a-26, a-25, a-24, a-23, a-22, a-21]
a-21: (J O):[a-26] (T I):[a-25, a-24, a-23, a-22, a-21]
a-22: (G A):[a-26, a-25, a-24, a-23, a-22, a-21]
a-25: (B U):[a-26, a-25, a-24, a-23, a-22, a-21]
a-24: nil:[a-26] (X I):[a-25, a-24, a-23, a-22, a-21]
```

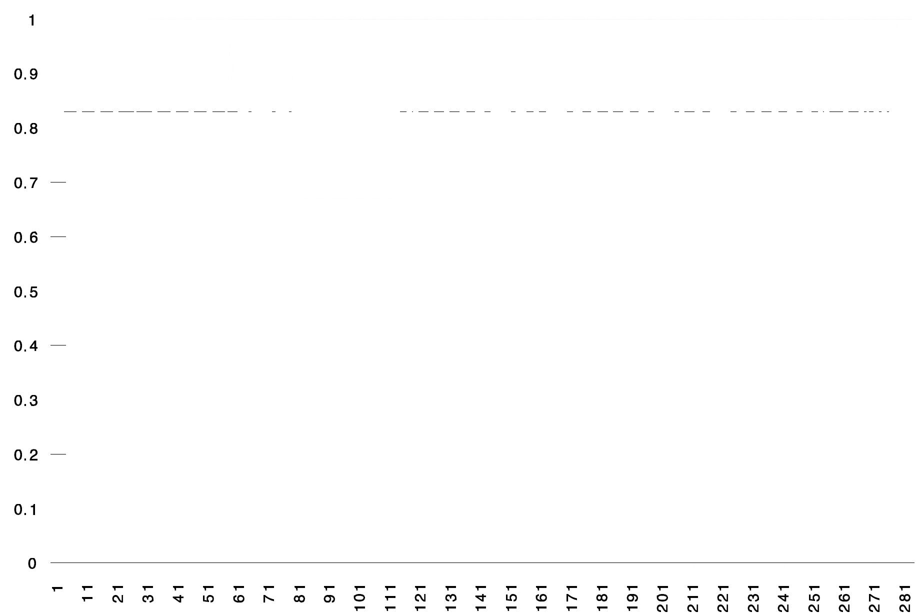

Figure 4: This figure gives an overview of the vocabulary acquisition by a new agent. The x-axis represents the number of conversations. The y-axis represents the percentage of agents using the same word for the same meaning. The new name for the agent climbs up from 0. In the upper left corner we see that the new agent quickly picks up the existing vocabulary

Here is an example of a dialog involving the new agent. a-26 uses its own name '(R E)' as part of a spatial description. a-26 also already required the meaning for '(B A)', which is a-23:

```
Dialog 7222 with a-26 a-25
 => a-26: (a-23)
   a-26: a-23 -> 'point at a-23' <- a-25: a-23
   a-26: a-26  -> (R E)  <- a-25: a-26
   a-26: FRONT  -> (X O)  <- a-25: FRONT
   a-26: RIGHT  -> (X E)  <- a-25: RIGHT
 => a-25: (a-23)
   a-25: a-23  -> (B A)  <- a-26: a-23
 => a-26: (a-23)
   a-26: confirm -> 'yes' <- confirm
```

The graphs in fig. 4 and 5 show the language acquisition process.

5 Conclusions

A mechanism has been presented in which a group of distributed agents develops a vocabulary to name themselves and to identify each other using spatial relations. Self-organization as opposed to genetic evolution has been used. Self-organization is a mechanism very common in biosystems for reaching coherence among a group of distributed processes. It is based on the amplification and

self-enforcement of fluctuations. The fluctuations consist here of random changes to the coupling between words and meanings. The changes are influenced by communicative success, leading to coherence. It was shown that a vocabulary indeed emerges in a group of agents through a series of conversations. The mechanism also copes with the entry of new agents or new meanings.

Additional experiments are currently being performed to explore issues like the formation of morphological and syntactic structures, the indirect mapping of meanings to words (where one word may capture many different meanings), the emergence and handling of ambiguity, the grounding of language in robotic agents, etc. Much work remains to be done before an

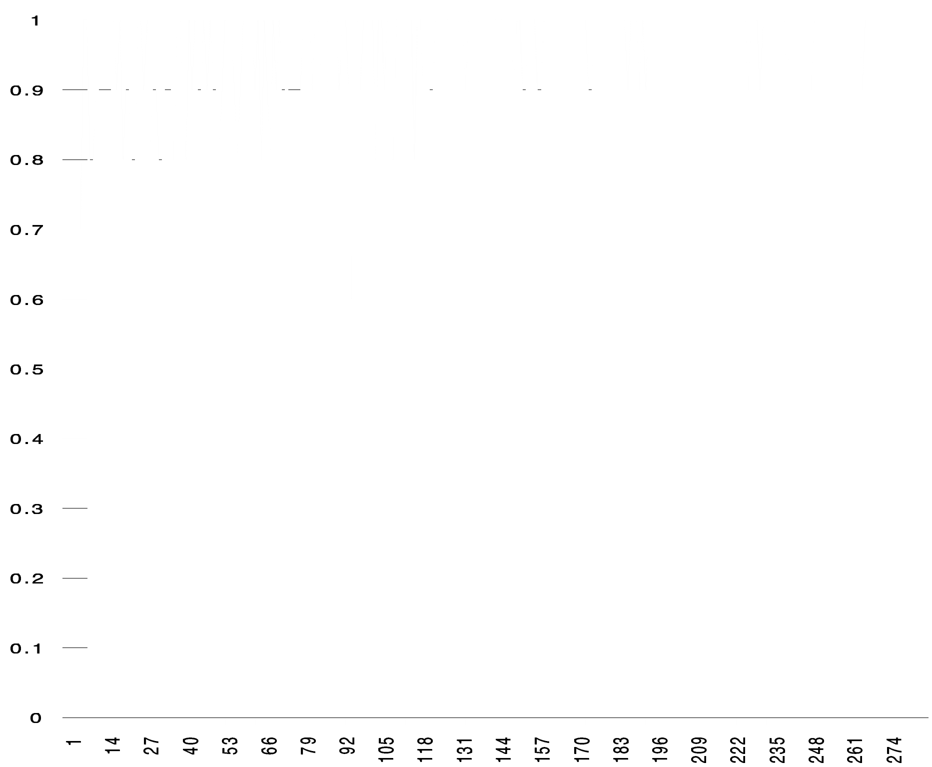

Figure 5: This figure plots the communicative success for the same process as fig. 4. The x-axis represents the number of conversations (per tens). The y-axis the communicative success. The entry of a new agent hardly affects the average communicative success.

alternative theory of language takes full shape. However it appears that a new exciting line of linguistic research has been opened up.

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