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'WHAT DID YOU SAY?' EMERGENT COMMUNICATION IN A MULTI-AGENT SPATIAL CONFIGURATION

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This paper reports the results of a multi-agent simulation designed to study the emergence and evolution of symbolic communication. The novelty of this model is that it considers some interactional and spatial constraints to this process that have been disregarded by previous research. The model is used to give an account of the implications of differences in the agents' behaviour, which are embodied in a spatial environment. Two communicational dimensions are identified: the frequency with which agents refer to different topics over time and the spatial limitations on reaching recipients. We use the model to point out some interesting emergent communicational properties when the agents' behaviour is altered by considering those two dimensions. We show the group of agents able to reach more recipients and less prone to changing the topic have the highest likelihood of driving the emergence and evolution of symbolic communication.

Keywords: Agent-based simulation; Computational sociology; Emergence; Lexicon acquisition; Symbolic communication.

1. Introduction

Human communication (from here on *symbolic communication*) is a key concept within sociological research and for many authors the scientific study of this process is of paramount importance to explain the emergence of social order. Most of the work done by prominent sociologists such as Blumer [1], Habermas [5] and Luhmann [7] has been devoted to comprehending the relationship between social order and the features of symbolic communication. Recently, Sawyer has claimed that a theory of social emergence needs an explicit understanding of symbolic communication [11, 12]. We have made similar claims for the case of computational sociology in [10]. Computational sociology [3] models social phenomena by using the ideas of emergent complex systems, although the very notion of emergence is a contentious element within the field. In order to overcome these quarrels, sociological theories of symbolic communication can be useful to computational sociology, since they give an account of the emergence of the social realm from the 'bottom up' as communication and describe the process by which society limits possible individual actions.

In this article we present a sociological framework that explains the emergence of symbolic communication by considering two evolutionary constraints (Section 2). In this explanation, the frequency with which agents refer to different topics over time and the spatial limitations on reaching recipients are of importance. Then, we describe an agent-based simulation that considers some spatial features and replicates the evolutionary pressures discussed (Section 3). We present the simulation results and discuss the implications for understanding the emergence and evolution of a shared lexicon among independent agents (Section 4). Finally, we present some conclusions (Section 5).

2. Understanding Communication

2.1. *The Evolution of Communication*

From a sociological point of view, symbolic communication is the basic element of social order [6, 5]. Symbolic communication is an emergent order that involves at least two agents: a speaker and a hearer. Analytically it emerges through a synthesis of three selections: the speaker selects some information from a range of possibilities; she or he instantiates it through some signal or linguistic medium (utterance); the hearer observes the speaker's conduct and understand or misunderstands this utterance and its informational content [6]. Of course, the hearer can accept or reject the information, but either way it might be said that the hearer understands the speaker's proposal.

Regardless of how counter-intuitive this might be, the emergence of symbolic communication is improbable. As Luhmann [7] argues, despite the fact that in everyday life communication is taken for granted, it must—if it comes about—overcome some obstacles. We will focus on two of them: (1) the individuality of consciousness and (2) the extension of communication beyond direct participants[a]. The first improbability is related with understanding; given that their bodies are separate (and consequently they do not have access to the other's mind), it is unlikely that one person can understand the *informational content* or *topic* that another person wants to communicate (i.e, what another person *means*). The second improbability is related with the spatial limitations of communication in reaching recipients; in other words, it is improbable that communication can get to more people than are present in a given situation.

However, regardless of these improbabilities, social order exists and we communicate daily. This is because social evolution has overcome these improbabilities with some mechanisms. The first improbability is solved by the emergence of *cultural signs*, like words, which make it more probable that individuals in interaction (and members of the same community) can understand each other. This is the case because both the individual using a cultural sign (the speaker) and the individ-

[a]There is a third improbability related with the difficulty of ensuring that the hearer accepts and follows the communication's informative content presented by the speaker's utterances, even though she understands it. In this paper, we will not discuss this improbability.

ual receiving it (the hearer) can identify the same topic. That is, cultural signs make more probable that the 'hearer' understands the 'speaker', because they can, through equivalent signs, reinforce the impression that they are attending to equivalent topics.

But cultural signs *per se* are still strongly coupled with interactional contexts; they require that the individuals that use them are near to each other because the 'hearer' *must* see or hear the sign used by the 'speaker' in order to distinguish its informational content. Consequently, there are important spatial constraints for the use of cultural signs. Thus, the second improbability refers to the problem of the limited range of communications. *Dissemination media* [7], such as writing, printing and electronic broadcasting, contribute to expand communication beyond the restrictive boundaries of interactional contexts (i.e., face to face interaction). In more abstract (and metaphoric) terms, the extension of communication beyond direct participants is a question of magnitude: how *loud* the speaker can 'utter' some cultural sign and consequently reach more recipients. To be sure, 'voice loudness' had no impact on the evolution of cultural signs. Rather, we are proposing the idea of 'loudness' might be (as we will see in section 3.2) a good operationalization to model the dissemination media's effect, that is, the capability of increasing the number of potential recipients one agent can reach in time and space.

2.2. *Different Communicative Strategies*

From the previous discussion we can state two general implications about the emergence and evolution of some symbolic communicative system. Firstly, in order to stabilise a cultural sign x over time, the number of times that individuals communicate about the same topic by using x must be crucial. Analytically, we can imagine a population where there are individuals that participate for longer in communicative interactions about the same topic (i.e., they seldom change the topic) and individuals that participate in different communicative interactions about different topics (i.e., they often change the topic). Secondly, because cultural signs are so tied to the restrictions in space (and time) of interactional orders, which are by definition ephemeral (see [4]), the agents' capability to reach more recipients must have important consequences for the generalization and stabilization of cultural signs over time. Analytically, we can imagine a population of individuals whose utterances are 'loud' (i.e., they can reach many recipients) and individuals whose utterance are 'soft' (i.e., they can reach few recipients). These two aspects might act as evolutionary pressures for the emergence of symbolic communication.

As we can see in Figure 1, symbolic communication can be characterized by the combination of two dimensions, namely: 1) the *frequency of changing the topic* (FCT) and 2) the *capability of reaching recipients* (CRR). Both dimensions are features of agents that have consequences for the emergence of symbolic communication. The first dimension is related to the rate that an agent can change the topic of her or his communication; agents in interaction can quickly or slowly vary the topic of communication over time and, consequently, the number of times they refer to the topic by using some cultural sign. The second dimension is related to the *'loudness'* of the agent's voice, that is, the capacity to reach more recipients beyond the direct participants in the interaction. The combination of these two dimensions produces four types of communicative strategies, as shown in Figure 1.

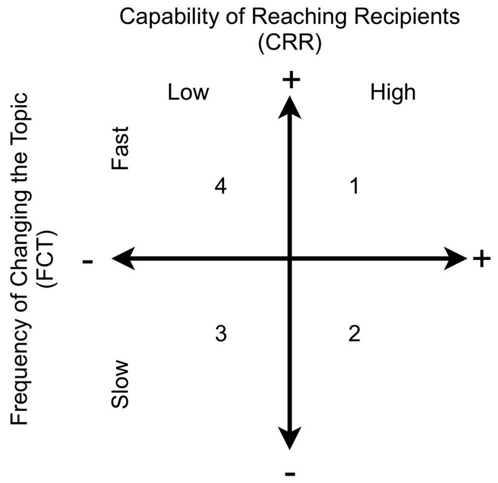

Fig. 1. Four Paradigmatic Communicative Strategies.

This framework poses some interesting research questions. In this article, we want to study one of them. If the capability of reaching recipients and the frequency of changing the topic are as important for the emergence of symbolic communication as sociological theory argues, then those dimensions must have some impact on the agents' ability to produce and disseminate their own cultural signs across the population. Specifically, there might be one communicative strategy that is more advantageous for spreading cultural signs than others.

3. The Simulation

In order to study the previous theoretical framework we have developed an agent-based simulation taking into account some spatial characteristics. The aim of this simulation is to clarify to what extent the two dimensions affect the emergence and evolution of symbolic communication. We want to understand whether those dimensions, and specifically the communicative strategies that the combination of them produce, have some effect on the agents' ability to generalise their own cultural signs. This simulation is based on existing research about the emergence of lexicons [8, 13–17]. According to Vogt and Coummans' [16] categorization, the communicative interactions between agents in our simulation resemble the *Observational Game*, in which the agents establish *joint attention* over one single object and then communicate about it. However, we make some important modifications to the observational game: (1) the agents are embodied in a spatial configuration, (2) they have different behaviours, and (3) communicative interactions can involve more than two agents.

By convention, in conformity with previous research in the area, the communicative system will be called a *shared lexicon*, a set of associations among meanings and cultural signs called *words*. A lexicon is shared by the whole population of agents at the end of the simulation. Our interest is in understanding which communicative strategy is best at allowing a group of agents to influence the shared lexicon. As a measure of success in disseminating words, we use the number of words that each communicative strategy, represented by a group of agents endowed with that strategy, inserts into the shared lexicon. Let us now define formally the main components of the model.

3.1. *Agent behaviour and Objects*

Let there be a set of agents $A = \{a_1, ..., a_n\}$ and a set of objects $O = \{o_1, ..., o_n\}$ placed within the world. The agent population is split into four groups g_i, where $i \in \{1, 2, 3, 4\}$. $\forall a : a \in A,\ a$ is assumed to see objects $o \in O$; produce utterances u_a consisting of a word w; hear the utterances u_n that other agents produce; and randomly move across the world.

An agent's utterance u_a have an *audibility radius* r_a. An agent's speed of movement is measured by the number of steps it takes in each simulation tick, the *step length* s_a. $\forall o : o \in O$, o is assumed to have a fixed visibility area v (i.e., all the objects have the same visibility area and the grid was built in such a way that the visibility areas do not overlap). Both r and s can vary between the agents according to their group membership.

In this model, the *audibility radius* r_a is our operationalization of the communicational dimension *Capability of Reaching Recipients* (CRR), because the larger an agent's audibility radius, the more recipients it can reach with its utterances. The second operationalization is less obvious. In this model, *step length* s is our operationalization of the communicational dimension *Frequency of Changing the Topic* (FCT). Because the objects are placed at regular intervals within the world and the agents are randomly moving across the world, the shorter the step length, the longer the agents will be participating in communicative interactions about the same object (either 'speaking' or 'hearing' about it).

3.2. *Communicative Interactions*

A communicative interaction I always involves one object $o \in O$ and two or more agents, where one of them is a speaker $s_a \in A$ (who utters a word w with a given r) and at least one is a hearer (or recipient) $h_{ai} \in A$, where i is the group to which h belongs, and $s_a \notin h_{ai}$. The hearer h_{ai} must both see the object and hear the speaker's voice. Therefore, $I = \{o, s_a, h_{ai}\}$. In each communicative interaction there is one and only one object visible to the agents and this object becomes the topic of communication[b].

3.3. *The Lexicon*

A word w is a sequence of four letters drawn from a shared alphabet, where the first letter identifies the group origin of that word and the three remaining letters are randomly chosen following the rule *Consonant - Vowel - Consonant*. The lexicon is implemented as an association between a word w and a topic o measured by a value σ called the *score*. Each time a word w is heard by an agent h_{ai}, the score for this word w and the topic o is increased or decreased depending on the result of the communicative interaction, called in this simulation the 'chatty game'[c].

The shared lexicon is operationalized as the words which are related with the topics at the end of the simulation. Because our model allows us to identify the group origin of each word, we can count the number of words that one group disseminates over the whole population.

4. Results and analyses

The simulation allowed us to explore the effects of varying the two parameters, Capability of Reaching Recipients (CRR) and Frequency of Changing the Topic (FCT), on the likelihood that an agent is able to spread its word-topic associations to other agents and especially to other groups. To study the effect of spatial location, the agents were given the ability to move on a square grid, divided into four quadrants coloured green, yellow, blue and violet. The region for each group of agents is represented by the corresponding colour. Groups of 10 agents were located at random positions on each of the four quadrants at the start of each run. During the simulation, the agents can move freely over the grid. Also located in each quadrant is one example of each of four objects: a flower, a leaf, a tree and a plant (represented by appropriately shaped icons). Figure 2 shows a view of the square grid.

Measurements on this grid are in pixel units. Each quadrant is 40 units wide (so the grid as a whole is 80×80). At each time step, every agent can move one step length, an agent per group is randomly selected to be a speaker and it attempts to carry out a Chatty Game with all the hearers within range, with the nearest object as the topic. The simulation continues until the emergent shared lexicon contains one word for each object (i.e., the shared lexicon contains four words). The model was built using NetLogo 4.0.4 [18].

[b] In the rare case an agent, speaker or hearer, is located over the boundary of two visibility areas, it selects one random object as the *chatty game's* topic.
[c] Although previous research has named this kind of simulation a *Language Game* (and our model is based on that research), we want to avoid the linguistic and even philosophical implications of that name. A detailed explanation of this kind of game is given in [16] .

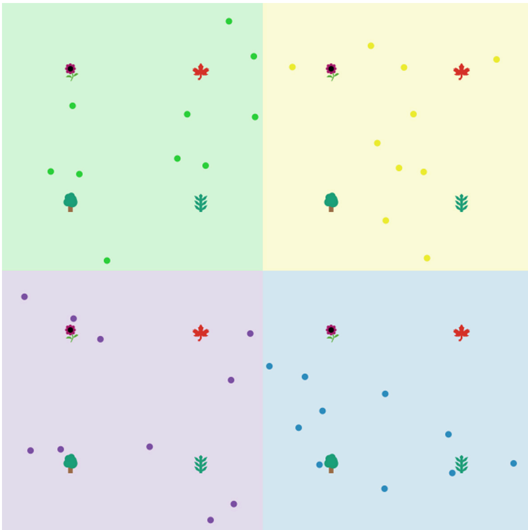

Fig. 2. View of the simulation

Experiments were carried out by setting the values of CRR and FCT of the agents in one quadrant, while leaving the values of these parameters for the agents in the other three quadrants at their arbitrarily chosen default settings (CRR = 13 and FCT = 0.7). 121 such experiments were performed, by sweeping the first quadrants' agents through combinations of CRR and FCT values, varying CRR from 8 units to 18 units, and FCT from 0.2 increasing by 0.2 to 1.2. The number of words coming from each group, as well as the number of words in the final shared lexicon, were averaged over 200 runs of each experiment. Statistical analysis on these results was then carried out using R [9].

Figure 3 shows the number of words in the shared lexicon at the end of the runs contributed by the experimental group, plotted against CRR and FCT. Using OLS regression, a best-fitting plane is also shown. The plane slopes negatively along the FCT dimension, showing that the greater the frequency of topic changing, the fewer words there are in the shared lexicon. The positive slope along the CRR dimension indicates that the greater the capability of reaching other agents, the larger the number of words in the shared lexicon. We conclude that a group of agents endowed with a high CRR and a low FCT would have the highest likelihood of spreading part or all of its word-topic associations to the other groups.

These correlations pose an obvious question: Why would 'speaking loudly' (high CRR) and 'moving slowly' (low FCT) have the highest likelihood of affecting the shared lexicon? We address this question by three consecutive steps: (1) we highlight several aspects that might influence the likelihood of affecting the shared lexicon; (2) we propose a way to measure these aspects and (3) we identify the extent to

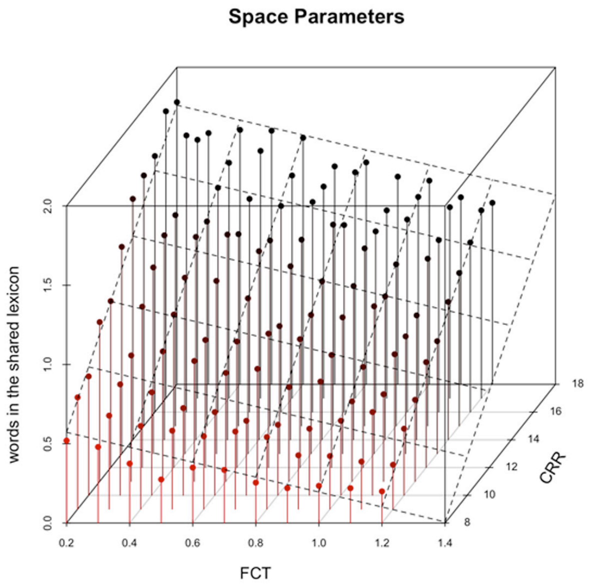

Fig. 3. Simulations Results.

which each of those aspects can alter the probability of spreading a word in the shared lexicon.

Beacause we want to look in great detail at the origin of a single word, our analysis is performed on a sample obtained by a single run of the simulation. For each time-step we recorded the speaker, the hearer(s), the topic of the conversation and the uttered word. Since we are interested in monitoring the process of creating a word and the way this spreads to the whole population, the data was filtered, first to focus on a single object (e.g., flower), and then to reject all data where the uttered word did not subsequently change. That is, we consider all data until the step where the final word for that object emerges. This is the point where the word reaches the highest score σ for that object in the lexicon. Figure 4 shows the number of words created for each object over time. The dot on each line indicates the point after which the uttered word does not change. At that point, all the agents already share a common word-topic association. This filtering permits clearer observation of the mechanisms involved in creating and spreading a certain word-object association.

We sampled a simulation with $CRR = 18$ and $FCT = 0.2$ for one group — in this case, the 'violet' group — and $CRR = 8$ and $FCT = 1.2$ for the other groups. According to the OLS regression shown in Figure 3, we chose this particular settings because it guarantees the highest probability that the word, associated to the selected object, comes form the experimental group. As expected, most of the

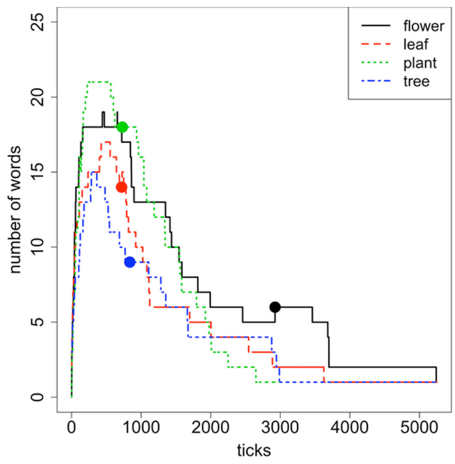

Fig. 4. Filtering Process Simulation 1.

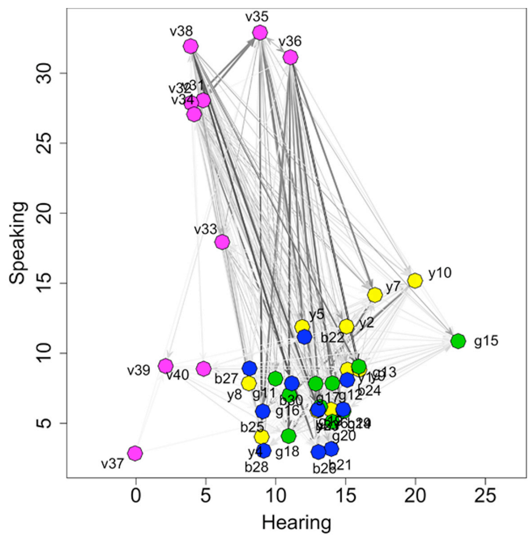

Fig. 5. Network Simulation 1.

words in the shared lexicon come from the violet group (three of four words, in this case for the objects flower, plant, and tree). Figure 5 shows the relations among agents who engaged in the process of creating and sharing the violet group's word for the object 'flower'. Dots represent agents, labelled and shaded according to their group (e.g. 'v' and 'light grey' stand for the violet group). Lines represent interactions, shaded according to the number of times the speaker has uttered a word to the hearer.

The network layout displays the number of agents that each agent has heard from (x axis) or spoken to (y axis).

Several features of the 'violet' group can be observed in Figure 5. Firstly, they are mostly on the left hand side of the plot; this means that they hear from fewer speakers than agents in other groups. Secondly, several agents from the 'violet' group are located at the top of the plot; this means that they speak to a greater number of agents compared to other groups. Thirdly, there is a high occurrence of reciprocal relations among agents of the 'violet' group because the links connecting them are darker. These observations allow us to highlight three characteristics that drive the evolution of the model: (1) the capability of hearing from other groups; (2) the capability of speaking to other groups; and (3) the mutual relations among agents within the same group.

In order to define the effect of these three aspects on the groups' capability of spreading their words we will formalize each of them. The capability of hearing from other groups H_g and the capability of speaking to other groups S_g are measured as follow:

Definition 1. Hearing capability of group g

Let P be the set of all groups. Let a be an agent of group g, and b be an agent of another group h. Let I_{ab} be the occurrence of the relation between a speaker a and a hearer b. Let HA_a be the hearing count of agent a, $HA_a = \left(\sum_{\forall b \in h \subset P - \{g\}} I_{ba} \right)$. Then:

$$H_g = \sum_{\forall a \in g} HA_a \tag{1}$$

Definition 2. Speaking capability of group g

Let SA_a be the speaking count of agent a, $SA_a = \left(\sum_{\forall b \in h \subset P - \{g\}} I_{ab} \right)$. Then:

$$S_g = \sum_{\forall a \in g} SA_a \tag{2}$$

These two measures give us an idea about the overall number of outgoing and incoming links from a group towards other groups, taking into account the occurrence of each 'chatty game'. The mutual relation between agents within the same group is measured using a definition of distance: the smaller the distance between two agents, the stronger is their mutual relation.

Definition 3. Mutual relation between two agents a and b from the same group g

$$r_{ab}^{g} = [(I_{ab} + I_{ba}) - |(I_{ab} - I_{ba})|] \cdot \frac{(I_{ab} + I_{ba})}{2} \tag{3}$$

Definition 4. Distance between two agents a and b from the same group g:

Let m be the maximum value of r_{ab}^{g} between all the pairs of agents within all the groups. Then:

$$d_{ab}^{g} = \frac{(m - r_{ab}^{g})}{m} k \tag{4}$$

The scalar k scales the measurement. For simplicity we assume $k = 100$. Finally, we classify the mutual relations between agents within the same group; the overall value of the mutual relation for each group is function of the number of pairs that engages in chatty games N and their distance d_{ab}^{g}. We define this last element as follow:

Definition 5. Overall mutual relation value for a group g

$$v_g = \sum \frac{(k - d_{ab}^{g})^2}{N} \quad \forall a, b \in g \tag{5}$$

The last step of the analysis is to find a relationship among the three characteristics H_g, G_g and v_g.

For each group, the greater the overall mutual relation value and the speaking capability and the smaller the hearing capability, the greater is the likelihood of affecting the shared lexicon. This relationship summarises our understanding of the mechanism involved in the evolution of the model. The next definition provides a measure to predict which group has the highest likelihood of affecting the shared lexicon.

Definition 6. Probability of affecting the shared lexicon for a group g

Let $L_g = \dfrac{(v_g \cdot S_g)}{H_g}$ be the likelihood of group g of spreading its own word topic association. Then:

$$p_g = \frac{L_g}{\sum_{g=1}^{4} L_g} \cdot 100 \tag{6}$$

Measurements made on the example run using these definitions are shown in Table 1 as Simulation 1. The p_g value for the 'violet' group is by far the greatest in Simulation 1 (99%). In order to test the validity of our analysis we performed another simulation where all the groups had the same value of CRR and FCT. In this scenario it is a matter of chance which group has the highest likelihood of spreading a word within the shared lexicon, because all the groups have the same parameters. However, performing the analysis presented above, the probability that a group affects the shared lexicon can be calculated. As example we consider the word associated with the object 'flower' in the shared lexicon, which, in this second simulation, comes from the yellow group. Figure 6 shows the filtering process, Figure 7 shows the relations among agents in the secon simulation and whereas Table 1 illustrates the measurements for this experiment.

Table 1. Simulation measurements.

	Simulation 1				Simulation 2			
	Yellow	Green	Blue	Violet	Yellow	Green	Blue	Violet
Measurements								
v_g	7.99	5.71	1.75	490.27	232.78	1.58	56.81	4.46
S_g	117	161	102	842	278	157	213	107
H_g	440	399	376	76	144	253	160	198
p_g	0.05%	0.04%	0.01%	99.9%	85.05%	0.19%	14.31%	0.46%

This analysis does not take into account an important aspect that drives the evolution of the model. It considers only already defined groups. What could be of interest to investigate is the role played by mixed groups. Sometimes the analysis shows that a certain group has a higher probability for affecting the lexicon, although the word in the shared lexicon comes from another group. This happens because there are mixed groups, where for instance an agent from the blue group exploits the high overall mutual relation value of the green group and spreads its own word in the shared lexicon.

5. Conclusions

In this paper we have reported a computer simulation about the emergence of symbolic communication that considers some spatial constraints. This simulation aimed to model the emergence of a symbolic communicative system over time in a way that reproduces two important evolutionary pressures: the improbability that one cultural sign means the same for different agents and the improbability that speakers can reach recipients beyond those present. Based on these improbabilities, we defined a theoretical model that combines two dimensions: the capability of reaching recipients, which was operationalized as the *audibility radius*, and the frequency of changing the topic, which was operationalized as the *step length*. The combination

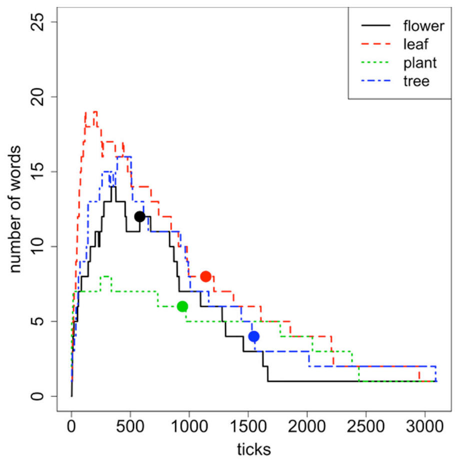

Fig. 6. Filtering Process Simulation 2.

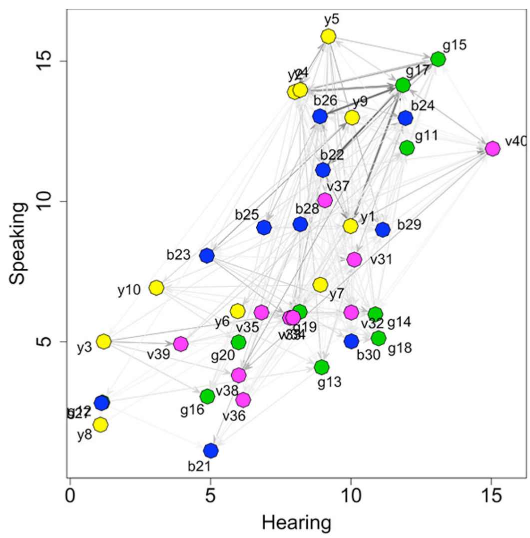

Fig. 7. Network Simulation 2.

of these two dimensions results in different communicative strategies, modeled here by different groups of agents. By using this simulation wee have clarified what agent behaviour most effectively spreads their own cultural signs across the population and by a further analysis we have explained why that is the case.

The model shows that the group of agents able to reach more hearers and less prone to changing the topic has the highest likelihood of affecting the shared lexicon.

In terms of agents' actions, that group manifests some sort of reiterative behavior: these agents perform many communicative interactions about the same topic. This behaviour leads these agents to share a strong word-topic association widely. The interaction of this group of agents with other groups (with different behaviours) brought about another effect: the agents are not particularly aware of the other groups' word-topic associations. They move around a small area, and hardly explore the rest of the world (i.e., they hardly change their topic). The spreading of their lexicon is in fact carried out by the other groups, particularly those which move more quickly (i.e., they frequently change their topic).

The results suggest two issues which demand further research. Firstly, we hypothesised that differences between group behaviours produce different 'communicative roles'. The simulation could represent a kind of social division of labour [2]: some clusters of agents are 'in charge' of spreading, whereas others are 'in charge' of creating strong relations between topics and words. Thus, in our model, agents' heterogeneity produces social homogeneity. Secondly, as stressed in section 4, the analysis indicates that ever when a certain group has a higher likelihood of spreading its lexicon, its shared cultural signs can actually have a different group origin. This could happen because there are mixed groups, when for instance an agent from the blue group exploits the high overall mutual relation value of the green group and spreads its own word in the shared lexicon.

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