Conventionalization of Linguistic Categories under Simple Communicative Constraints

Tao Gong, Andrea Puglisi, Vittorio Loreto, and William S-Y. Wang

***Abstract*—The language game approach is widely adopted to study conventionalization of linguistic knowledge. Most of contemporary models concentrate on the dynamics of language games in random or predefined social structures, but neglect the role of communicative constraints. This paper adopts one form of language games, the category game, to discuss whether some simple distance-related communicative constraint may affect the conventionalization of linguistic categories. By comparing the simulation results with those based on another form of language games, the naming game, we point out some essential differences between these two games which cause their distinct performances under the same communicative constraint. This study fills the gap between the dynamics of language games in random structures and that in complex networks, and suggests that internal properties of language games may reversely influence communicative constraints and social structures.**

I. Introduction

OUR social behaviors, such as language, have evolved primarily via contact with a limited number of other individuals, and a prerequisite for successful language use is conventional linguistic knowledge [1]. But where do these conventions come from, and how do they evolve through iterative communications? Many theoretical and practical studies have discussed these questions to better understand the evolution of human communication system (e.g., [2]–[7]), among which *the language game approach* [8] serves as an efficient method to study *conventionalization* (a process of social agreement by conforming one's language to that of the others or the community [9]) of various linguistic components during language evolution.

This approach views language as a *Complex Adaptive System* [11][12]. It usually postulates a population of agents and an interaction protocol between them, called a *language game* [10]. Using this game, agents can carry out some communicative task, such as drawing another' s attention to an object in their surroundings. Agents typically establish a communication system from scratch, by inventing new forms of conceptualization and/or expression, and adjusting their available knowledge based on its utility, frequency, or social prestige. Through a number of iterated communications among agents, a set of linguistic knowledge gradually become conventional in the population, and further statistical analyses can examine the dynamics of this game and provide some quantitative understanding of language evolution.

Many forms of language games have been proposed to study conventionalization of various types of linguistic or general cognitive knowledge. For instance, *the naming game* [13] studied the emergence of coherence, in which, to draw attentions to each other, speakers and listeners create various names for a particular object, and once they successfully use a common name for that object, they will eliminate all other competing names, but leave the common one. Otherwise, the listener will acquire the speaker's name as a candidate in his/her inventory. After a number of naming games, the population converges to a common object-name pair. *The category game* [14] (which will be reviewed in Section 2.A) extended the naming game by allowing agents to categorize in a continuous semantic space and create corresponding word labels for their categories. Through iterated category games, a set of linguistic categories can be gradually shared in the population.

In addition to many successful strategies reviewed from these language games, statistical physicists further explored the dynamics of these games by putting agents into random networks, 1D/2D lattice, or other complex structures like scale-free [15] and small-world [16] networks (e.g., [14][17][18]). These studies convincingly discussed the role of social structure in converging linguistic knowledge, but most of them neglected the reverse role of language games in social structure; since in these studies, a successful or failed language game does not affect individuals' predefined social connections.

As a social phenomenon, linguistic interactions can affect not only participants' knowledge but also their social connections. Accumulative failed or successful interactions may weaken or strengthen social connections. During interactions, local communicative constraints, such as geographical or social distance, may adjust the probabilities for different agents to interact with each other, thus affecting individual or group similarities on a global scale [19][20]. These constraints, taking place much earlier than the emergence of complex social structures, could cast their influence on formation of mutual understanding and social structures. Without a careful study of these simple constraints and their roles on language evolution and social structures, it seems premature to proceed from random networks directly to complex structures, since different language games may

Manuscript received December 12, 2007. This work was supported in part by the EU under RD contract IST-1940 (ECAgents).

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978-1-4244-1823-7/08/$25.00©2008 IEEE

lead to different social connections, and the same structure may not always trigger similar effects on conventionalization based on different games.

Considering these, we present in this paper a simulation study exploring conventionalization of linguistic knowledge under simple communicative constraints. As an extension to our previous work [21] examining conventionalization of lexical knowledge based on the naming game, this paper concentrates on conventionalization of linguistic categories based on the category game. Through comparing the simulation results with those based on the naming game, we notice some distinct performances of these games under the same communicative constraint. The essential differences in the communicative tasks involved in these games could explain these different performances, which indicate that the internal properties of language games could influence the effect of communicative constraints and further affect the role of social structures. These findings will guide the future study on the dynamics of language games in complex networks, and contribute to the discussion on the mutual influence between communication and social structures.

The rest of the paper is organized as follows: Section 2 briefly reviews the category game, and introduces the distance-related communicative constraint; Section 3 discusses the simulation results of the two experiments under this constraint; Section 4 compares the naming game with the category game, and illustrates their different ways of conventionalization; and finally, Section 5 gives the conclusions.

II. The Category Game and Distance Constraint

A. The Category Game Review

Categories are fundamental to recognize, differentiate and understand the environment. Semantic categories, like other linguistic components, are culture-dependent conventions shared among a group of individuals [22], and the emergence of them may undergo a self-organization process via iterated interactions among individuals [23]. Different individuals may perceive or conceptualize the world differently, and establish different semantic categories. Through interactions, the boundaries of these categories tend to align, and their word labels tend to converge. Then, individuals can understand each other to a certain degree. The category game was proposed to theoretically simulate this alignment and convergence process, and demonstrate conventionalization of linguistic categories having both similar semantic ranges and common lexical labels.

In the model of the category game, N individuals are given stimuli from a single analogical perceptual space, these stimuli are represented by real-valued numbers ranging from 0.0 to 1.0. A *perceptual categorization* is a partition of the interval [0.0, 1.0] into discrete sub-intervals. Each agent has a dynamical inventory of word-meaning associations linking perceptual categories (meanings) with labels (words). All agents are initialized with a trivial perceptual category [0.0 1.0] and no words. Through pair-wise category games, the perceptual categories and their associated words coevolve dynamically among agents in the population.

In a category game, two agents are randomly selected, one as the speaker and the other as the listener (hearer). Meanwhile, M ($\geqslant 2$) stimuli from the perceptual channel are presented. The speaker discriminates these stimuli, and names one of them (topic). Then, the listener tries to guess the topic from other contextual stimuli based on the word produced by the speaker and his/her own inventory of perceptual categories. An individual's discrimination ability is restricted by his/her perceptual power, which is denoted by d_{min}, i.e., the minimal numerical distance required for discriminating two stimuli. In a single game, the minimal distance between any presented stimuli is d_{min}, but in general, stimuli can take any numerical value, constrained only by the numerical precision used in the experiment. In a category game, both participants' categories and the words associated to these categories can be adjusted, which are illustrated by two examples of the category game shown in Fig. 1.

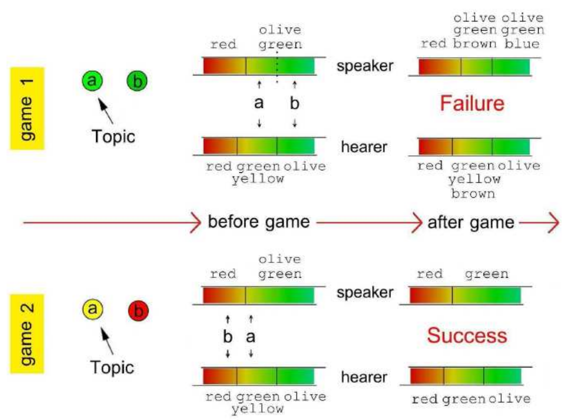


Fig. 1. Two examples of the category game (adapted from [14]). The round objects are stimuli presented in these games, among which the topics are pointed. The colorful banners represent individuals' perceptual spaces, and different individuals use different bars to partition their spaces into different perceptual categories, whose inventories of words are listed above or below.

In game 1, since the two stimuli fall into the same perceptual category, the speaker discriminates the chosen topic ("a") by creating a new boundary in his/her rightmost perceptual category at the position (a+b)/2. Then, two new categories are created, both inheriting the word-inventory ("green" and "olive") of their parent category, and a new word is invented for each of these new categories ("brown" and "blue"). Then, the speaker browses the list of words associated to the category that contains the topic. There are two cases here: if a previous successful game occurred with this category, its last winning word is chosen; otherwise, the newly created word ("brown") is chosen, and sent to the listener. Since the listener does not have this word in his/her inventory, this category game fails. Then, the speaker points at the topic, and the listener discriminates the topic, and adds the speaker's word to the inventory of his/her corresponding category.

In game 2, these two agents carry out another category game. The speaker chooses the topic "a", which is already discriminated in a perceptual category whose last winning word is "green". Then, the speaker sends this word to the listener. The listener also knows this word, and points at the topic that is contained in his/her corresponding perceptual category. This category game is successful. And then, both the speaker and listener eliminate all competing words in their used perceptual categories (the boundaries of these categories might still not exactly match), leaving the word "green" only. If ambiguity occurs in a sense that the speaker's word is associated to more than one category that contains the topic, an unbiased random choice is taken by the listener.

Based on these discrimination and learning mechanisms, a coevolution of perceptual categories and their words take place in a fully-connected network, which are briefly summarized in Fig. 2.

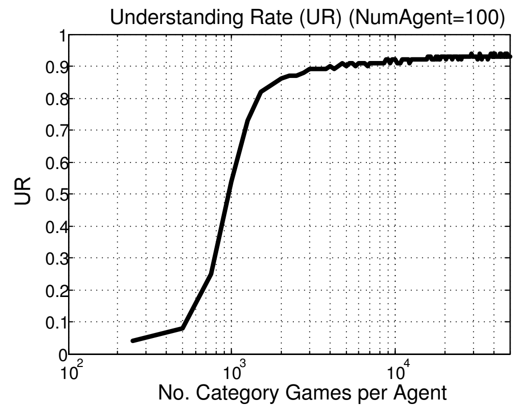
Fig. 2(a) traces the *Understanding Rate* (*UR*, similar to the Success Rate defined in [14]) that measures the percentage of successful category games between all pairs of agents in the population after a number of category games. To measure *UR*, agents play "virtual category games" without updating categories or their associated words, and the percentage of the successful game in all these virtue games is calculated. As shown in Fig. 2(a), in the logarithm axis, *UR* starts from a low value, which indicates that agents at this phase do not understand each other very well. And then, *UR* undergoes a sharp transition increasing over 0.9, which shows that agents at this phase can understand each other based on a common language. Perceptual categories keep evolving, since the creation of new categories may occur when agents discriminate topics from other contextual stimuli. However, the high value of *UR* illustrates the emergence and conventionalization of a set of *linguistic categories* (a number of perceptual categories whose last winning words are identical and whose perceptual boundaries are well aligned among individuals). This phenomenon is partially caused by the spreading of common words to the perceptual categories with adjacent boundaries (*the "word contagion" phenomenon* [14]).

The alignment of perceptual or linguistic categories is calculated by *the overlap function* as in Eq. (1), where *lc* is the width of category *c*, c_i is a category of player *i*, and c_{ij} is the category intersection set obtained based on the category boundaries of both players *i* and *j*. o_{ij} indicates the degree of alignment between categories in players *i* and *j*, which will reach 1.0 when the boundaries of these two sets of categories are identical:

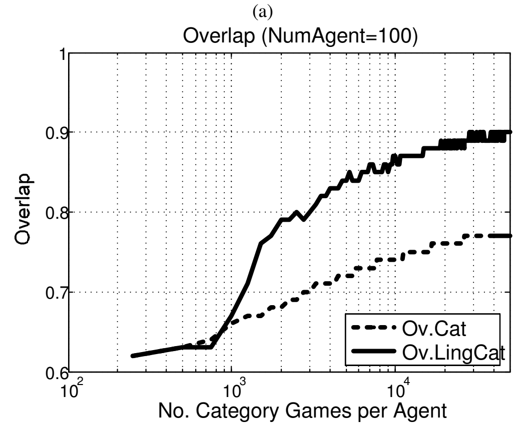
$$O = 2\sum_{i<j} o_{ij} / (N(N-1)), \quad o_{ij} = \frac{2\sum_{c_{ij}} (lc_{ij})^2}{\sum_{c_i} (lc_i)^2 + \sum_{c_j} (lc_j)^2} \qquad (1)$$

Fig. 2(b) traces the overlap value of perceptual categories and that of linguistic categories (the perceptual categories with identical last winning words) among all pairs of agents. The low value of the former shows that perceptual categories keep changing and their boundaries are not well aligned, but the high value of the latter illustrates the emergence of conventional linguistic categories that not only have well aligned perceptual boundaries but also common words. Based on these linguistic categories, when playing the category game, agents can have a high value of *UR*.

Fig. 2(c) lists a set of conventional linguistic categories emerged in the population after a number of category games. Each of these linguistic categories may consist of many perceptual categories, whose boundaries are adjacent and all share the same last winning words. Although these linguistic



(a)



(b)

```
Game=5000000
NumComLingCat= 15;
LingCat [  1]: LastWinWord= 1112, Range[0.00 0.03)
LingCat [  2]: LastWinWord= 2054, Range[0.06 0.08)
LingCat [  3]: LastWinWord= 2475, Range[0.10 0.15)
LingCat [  4]: LastWinWord= 3224, Range[0.18 0.23)
LingCat [  5]: LastWinWord= 3634, Range[0.26 0.28)
LingCat [  6]: LastWinWord= 1200, Range[0.31 0.35)
LingCat [  7]: LastWinWord= 4034, Range[0.39 0.41)
LingCat [  8]: LastWinWord= 3860, Range[0.42 0.44)
LingCat [  9]: LastWinWord= 2464, Range[0.47 0.56)
LingCat [ 10]: LastWinWord= 2200, Range[0.60 0.67)
LingCat [ 11]: LastWinWord= 3585, Range[0.71 0.74)
LingCat [ 12]: LastWinWord= 1158, Range[0.76 0.80)
LingCat [ 13]: LastWinWord= 1549, Range[0.83 0.87)
LingCat [ 14]: LastWinWord=  649, Range[0.88 0.92)
LingCat [ 15]: LastWinWord= 1067, Range[0.94 1.00)
```

(c)

Fig. 2. The results of the category game with N=100, d_{min}=0.01, and 200 sampling points: (a) the *UR* curve, which reaches 0.9 around 3000 games per agent; (b) the overlap value of perceptual categories (the dashed line) and that of linguistic categories (the solid line); (c) a set of conventional linguistic categories emerged in the population after 5×10^6 category games, *LastWinWord* records the words associated to these categories, and *Range* records the perceptual boundaries of these categories.

categories do not give a complete partition of the whole perceptual space, they are already sufficient to discriminate two randomly chosen stimuli from the perceptual space. These shared linguistic categories also keep evolving, and given more category games, they may cover almost the whole perceptual space.

The detailed explanations and statistical analyses of the dynamics of the category game in fully-connected networks can be found in [14]. In this paper, we directly borrow this form of language game, and study conventionalization of linguistic categories under a distance-related communicative constraint.

B. The Communicative Constraint

In our simulations, agents are put into a 2D torus X^2 (X is the side length of this torus). They can take discrete positions in X^2, and one position can have at most one agent. After playing a language game, an agent can move to one of its 8 unoccupied, adjacent discrete locations. Torus is different from other 2D special structures: in a torus, if agents at the rightmost (leftmost, top, or bottom) positions move further right (left, up, or down), they will reappear in the leftmost (rightmost, bottom, or top) positions. This torus structure can represent either a physical world or a virtual one, such as distributions of opinions or social status.

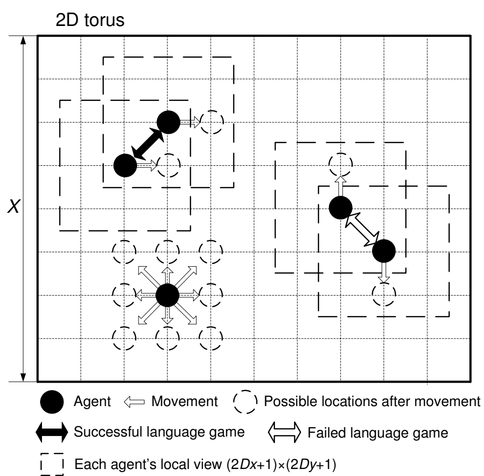


Fig. 3. The 2D torus with moving agents.

A distance-related communicative constraint is defined as follows: in a X^2, language games only take place between agents whose coordinates are within a limited block distance (D_x and D_y), as shown in Eq. (2) and Eq. (3), where x_i, y_i are agent i's coordinates in X^2, and the second part of each equation calculates the situations where agents are located in the boundaries of the torus, but their block distance may be still within D_x and D_y:

$$|x_i - x_j| \le D_x \text{ or } |x_i - x_j - 0.5X| \le D_x \quad (2)$$

$$|y_i - y_j| \le D_y \text{ or } |y_i - y_j - 0.5X| \le D_y \quad (3)$$

D_x and D_y can represent either a geographical constraint such as the city-county distance, or a social constraint such as dissident opinions. It acts like an individual's local view, based on which, an agent can contact at most $(2D_x+1)\times(2D_y+1)-1$(itself) other agents, if all of them are in its nearby locations. If D_x and D_y equal to 1, each agent can only interact with those lying in its 8 adjacent locations. This distance constraint also provides a bias in agent movement: if a language game between two agents is successful, they tend to bind together by moving jointly to maintain their block distance within D_x and D_y (i.e., if either of them moves, it tends to move to one of its unoccupied, adjacent locations (if any) so that their block distance after the movement is still within D_x and D_y); if the game fails, this binding may break down (i.e., if either of them moves, it moves randomly to one of its unoccupied, adjacent location (if any)). This constraint is local, much simpler than those defined by global complex networks. It may trigger the emergence of social clusters, each of which contains some agents who share similar linguistic knowledge but may not necessarily interact directly with each other. These clusters and their shared linguistic knowledge provide prototypes of complex social structures and their communal languages.

This communicative constraint can affect interactions among agents from two aspects: a) *the local view*, an agent cannot interact with others outside its local view; and b) *the movement bias*, through which, agents can contact others which are previously outside its local view, and form clusters. To evaluate the effects of this constraint on formation of conventional linguistic knowledge, similar to [21], we carry out two experiments. In Exp. 1, 100 agents are located in a 10^2 torus (every location in the torus is occupied by an agent), and D_x and D_y range from 1 to 10. In Exp. 2, 100 agents are put into tori whose side length X ranges from 10 to 90, but D_x and D_y are fixed to 5. In every time step of these experiments, all agents are selected one by one following a random sequence. Once an agent is chosen, it will play a category game with one of the others lying within its distance constraint (if any). After that, it will move (only in Exp. 2), based on the game result (successful or failed), to one of its unoccupied, adjacent positions (if any).

The total number of time step is 5×10^4, and the maximum number of possible category games is 5×10^6 ($5\times10^4\times100$), comparable to the settings in Fig. 1. The actual number of interactions depends on D_x and D_y, as well as X. In each simulation, we set up 200 sampling points; after every 250 time steps, some indices to evaluate the system performance are calculated. These indices include UR, the overlap values of linguistic categories among all agents, and N_T , which is defined as the number of time steps required for the overlap of linguistic categories to reach 80% of its maximum value in the whole simulation. We assume that the conventional linguistic categories having such a high value of overlap can already help agents to achieve a relatively high degree of mutual understanding. In each condition of the experiments, the results of 20 simulations are collected for statistical analysis.

In the following sections, the simulation results of these two experiments are discussed.

III. THE SIMULATION RESULTS

A. Exp. 1: different distance constraint (D_x and D_y)

In this experiment, all agents lie in a 10^2 torus, and D_x and D_y change from 1 to 9 with a step of 2. In all simulations, a set of linguistic categories emerge in the population, and Fig. 4 illustrates the dynamics of the category game in Exp. 1 and the statistical results under different constraints.

These results are similar to those based on the naming game reported in [21]. On the one hand, with the increase in D_x and D_y, the conventionalization of linguistic categories is accelerated, since agents in the population have bigger local views, and they can interact with a larger number of other agents in a bigger neighborhood to align their perceptual categories and acquire common words for these categories. On the other hand, when D_x and D_y are big, since agents can already interact directly with all others in the population, the acceleration of the conventionalization becomes inexplicit.

Besides these similarities, there is a small difference between the results in the category game and those in the naming game. In the condition of naming game, the acceleration effect becomes inexplicit only after D_x and D_y are greater than 4, i.e., only after agents can directly interact with all others in the population. In the condition of category game, however, once D_x and D_y are greater than 3, i.e., once agents can interact with about half (48) of the whole population, the conventionalization is already similar to that in situations where agents can interact with the whole population.

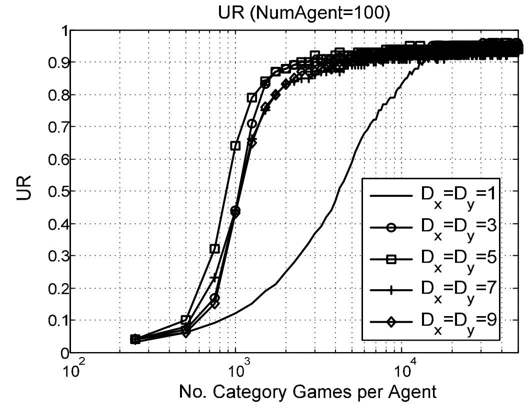
B. Exp. 2: different torus size (X)

In this experiment, 100 agents are randomly located in tori whose side lengths range from 10 to 90 with a step of 20. The possible locations for agents increase nonlinearly from 100 to 8100 in these tori, but the individual's local view (the distance constraint D_x and D_y) remains at 5. In all simulations, after a number of category games, a set of conventional linguistic categories emerge in the population, though the efficiency of conventionalization differs, as shown in Fig. 5.

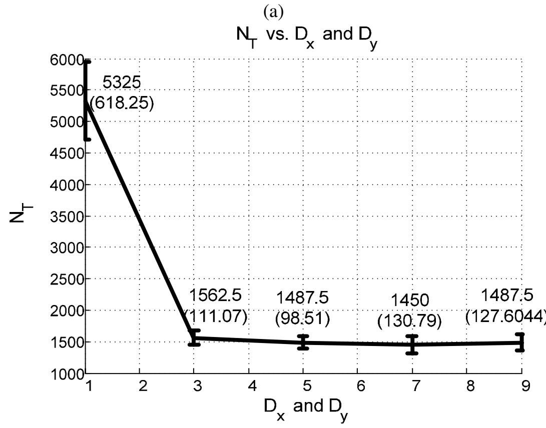
Similar to [21], with the increase in the size of the torus, the time steps required for a good degree of mutual understanding (over 80% successful) increase nonlinearly, and both the increase in *UR* and that in the overlap of linguistic categories are delayed.

Besides these similarities, there is a big difference between these results and those based on the naming game. In the results of the naming game, a "local convergence, global polarization" phenomenon [19] is shown in a big torus: agents gradually form some clusters, and those within clusters can clearly understand each other via a shared name, but those between clusters do not, due to using different names. This phenomenon is illustrated by a low *UR* value of the whole population. It may partially reflect the coexistence of many languages in the world, though these "languages" (with a single word) in the simulation could be short-lived.

In the results of the category game, the phenomenon of linguistic divergence does not occur: after a number of category games, even in a huge torus (X=90) much bigger than the one (X=55) used in the naming game simulations, agents can achieve a set of conventional linguistic categories that have high values of *UR* and overlap. This suggests that the communicative constraint does not form stable clusters to restrict agents from freely interacting with each other. This suggests that based on the category game, the movement bias



(a)



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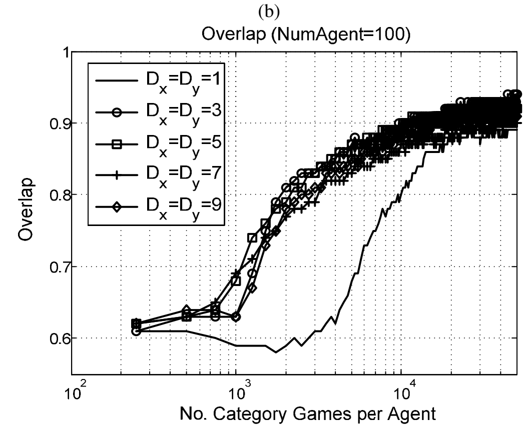

(c)

Fig. 4. The statistical results of Exp. 1: (a) the *UR* curves in conditions with different D_x and D_y, each line representing one simulation in each condition; (b) the average N_T in conditions with different D_x and D_y, (the numbers outside the brackets are the average values, and those inside the brackets the standard deviations); (c) the overlap values of linguistic categories in conditions with different D_x and D_y, each line corresponding to one simulation in each condition.

in the communicative constraint does not help much to form social clusters to restrain agents from contacting others.

Combing the results of both Exp. 1 and Exp. 2, it seems that the communicative constraint does not play any significant role in affecting the dynamics of the category game; the process of conventionalization follows a similar routine as that in the random network, and what this constraint does is simply to delay the conventionalization by confining agents from directly interacting with each other. Then, shall we conclude that this constraint is useless to affect the conventionalization of linguistic knowledge? No! As shown in [21], the very same constraint plays a significant role in the naming game in Exp. 2: it can separate agents into clusters, each using a particular name, and maintain these clusters in a relatively long time (although given a much longer time, some of these clusters or the whole population might converge). Therefore, there must be some internal properties in the naming game and category game that cause their distinct performances under the same constraint.

In the next section, we will compare these two types of language games, point out these essential differences, and discuss their reverse role on the communicative constraint and social structures.

IV. Discussion

Both the naming game and category game were proposed to abstract the self-organizing process of conventionalization of lexical or categorical linguistic knowledge. Both of these language games adopt some similar mechanisms to update individuals' linguistic knowledge. For instance, each agent has an inventory with an unlimited size to store various names, perceptual categories and words associated to these categories. If necessary, agents can randomly create a name describing a particular object, or a word associated to a perceptual category that contains a particular topic. If a game is successful, both participants eliminate all the competing names or words, but leave the successful one used in that game. If a game fails, the speaker always clarifies the topic by pointing, and the listener always adds the name or the word used by the speaker to his/her inventory.

Apart from these similarities, there are essential differences between these two forms of language games.

In the naming game, the object to be named is fixed, what differs are the names to call it. In addition, each candidate name for the object is randomly created and independent. Two agents can make their inventories converge after few naming games. Once converged, without much external interference from other agents, the future naming games between these agents are always successful. Even if it is broken down, this convention can be quickly reestablished within a limited number of naming games.

In the category game, however, the topic and other contextual stimuli are randomly selected from a continuous perceptual space. Given various contexts, agents may not only partition the perceptual space differently to categorize the same topic, but also associate different words to the related categories. Due to the uncertainty of topics, contextual stimuli, perceptual categories, and associated words, the

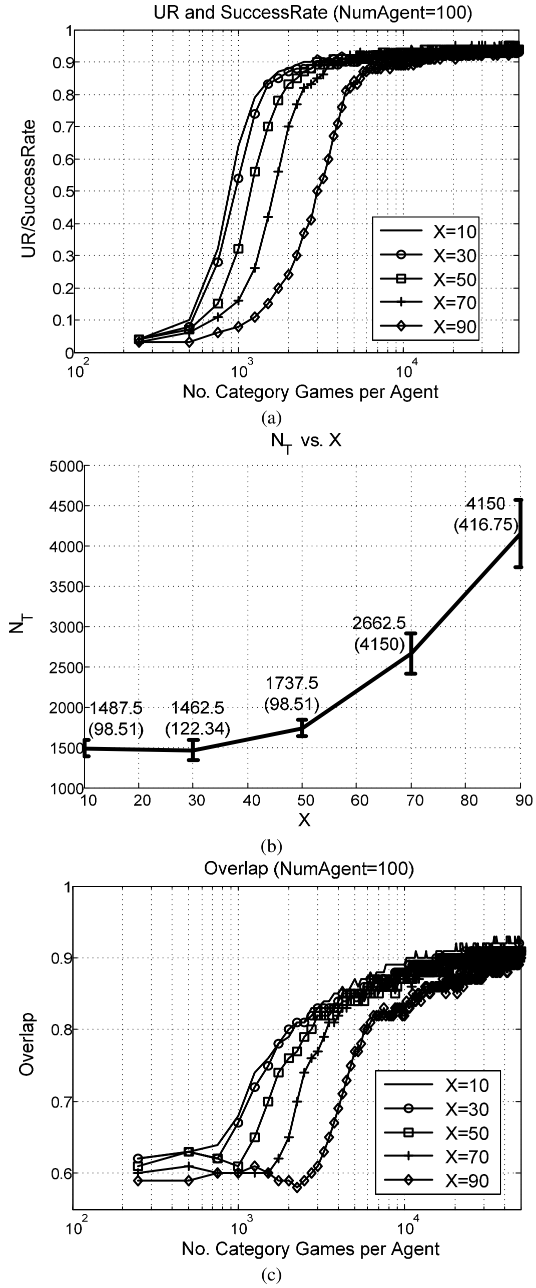

Fig. 5. The statistical results of Exp. 2: (a) the *UR* patterns in tori with different side length *X*, each line representing one simulation in each condition; (b) the average N_T in tori with different side length *X* (the numbers outside the brackets are the average values, those inside the brackets the standard deviations); (c) the overlap values of linguistic categories in tori with different side length *X*, each line corresponding to a simulation in each condition.

creation of new categories, the alignment of available ones, and the "word contagion" in individuals' inventories will continue for a long time, though they considerably get slower and slower, and finally become unperceivable. Therefore, without external interference, the acquisition of categorical knowledge to discriminate various topics between two agents cannot be efficiently achieved within a limited number of category games, even though these agents are endowed with identical discrimination and learning mechanisms. It is utterly impossible to experience all stimuli in the continuous perceptual space. A temporary solution to achieve a certain degree of mutual understanding is to roughly partition the whole space into a few discrete categories, and associate a common word to each of them across individuals. This solution is largely determined by the repertoire of external stimuli, and the internal properties of the communicative task in the category game [14]. The partition of some semantic domain, such as colors, may follow a similar routine; a few of color categories are established to partition the continuous color space into discrete subintervals, and across languages, the number of basic color terms are similar [24][25].

Considering these different properties, a successful naming game can clearly indicate the convergence of two agents' lexical knowledge, and the movement bias based on it is a good factor to form and maintain social clusters. However, the success of a single, or even a few category games is insufficient to indicate the convergence of participants' categorical knowledge, and the same movement bias cannot play a similar role to build up social clusters.

The internal properties of these language games may further affect the role of social structures that provide complex topological constraints. For instance, since coherence can be efficiently established via a limited number of naming games, agents with many social connections (hubs) are important to drive the convergence of the whole population. Meanwhile, based on the simple, distance-related communicative constraint and some naming game-like interactions, similar complex networks could be triggered. These conclusions have been exemplified in studies of lexical convergence and language change in complex networks (e.g., [18][26]). However, using the category game, the hub's role may become inexplicit in the same timescale, and it is difficult to predict the global structures under the same communicative constraint. Therefore, without clearly examining the internal properties of language games and their relations with local communicative constraints, we should not directly play various language games under the same predefined, global social structures.

V. Conclusion

This paper presented a computational study discussing conventionalization of linguistic categories based on the category game under a simple communicative constraint. This aspect of the research has been largely neglected, since most contemporary models directly adopt complex networks to study the role of social structures on the dynamics of language games.

Based on simple simulations in two experiments and a comparison between the results using the naming game and those using the category game, we point out that different properties of the communicative tasks involved in language games may cause some distinct performances under the identical communicative constraint. Local language games may influence the effect of communicative constraints, and play some role in global social structures. This conclusion extends the discussion on the mutual influence between communication and social factors. When designing future work exploring the social structure effects on language evolution, we should consider not only the relevant social structures which might shape the communal language in the population, but also the internal properties of the adopted language games. The study on internal properties of language games and their performances under various communicative constraints is also helpful to examine the effect of particular constraints, and to review some social strategies that maintain the structure based upon these language games and communicative constraints. This line of research could be insightful to study of language change, competition or death (e.g., [27][28]).

Acknowledgment

The authors would like to thank Dr. Andrea Baronchelli from Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, Barcelona, Spain, for providing the source codes of the category game and useful discussions relevant to this work.

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