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Emergence and evolution of language in multi-agent systems

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Abstract

Human language provides a highly efficient communication system, which emerged due to cultural interactions. To understand this still mysterious process, various interdisciplinary efforts are being made, which refer to evolutionary linguistics, evolutionary game theory or cognitive sciences. A promising approach considers language as a collective phenomenon, which emerges in a population of communicating agents. Numerous papers based on computational modelling demonstrate ubiquity of spontaneous linguistic synchronization among such agents. The approach got considerable impetus with the introduction of the so-called language game models. Their important feature is the horizontal nature of interactions between agents, which interplay within one generation only and do not create offspring, to whom they would transfer their linguistic skills. Recently, more sophisticated approaches are being developed with agents equipped with some cognitive abilities, employing, for example, reinforcement learning. Such a framework originated from Lewis signaling game, which was adapted to language evolution with subsequent extensions implementing, for example, Bayesian inference, neural networks or deep learning. Models with the reinforcement learning may combine single-generation language games with intergenerational learning, and certainly deserve further studies. The present paper provides a brief review of this interesting and rapidly developing research field.

Keywords: Multi-agent systems; Language emergence; Protolanguage; Language evolution

1. INTRODUCTION

The origin and evolution of language, which according to some researchers is the most significant distinguishing feature of a human, is an intriguing scientific problem and attracts much attention from researchers in multiple disciplines (Christiansen and Kirby, 2003; Dor et al., 2014; Hurford, 2014; Laks et al., 2008; Oudeyer, 2006; Progovac, 2015; Reboul, 2017; Żywiczyński, 2018). A very promising approach considers language as a system, probably having some adaptive features (Christiansen and Chater, 2016; Pinker and Bloom, 1990), which emerges in a group of communicat-

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ing individuals and whose properties may be a consequence of the cognitive skills of its users and of the nature of the interactions between them. Such a standpoint in fact encourages the study of language evolution using computer simulations, where one examines a population of artificial agents which interact autonomously with the environment and communicate among themselves (Cangelosi and Parisi, 2002; Gong et al., 2014; Lipowska, 2016; Nolfi and Mirolli, 2010; Steels, 2012). In such a complex adaptive system (Ellis and Larsen-Freeman, 2009; Steels, 2000), without any external stimulus or coordination, an efficient communication system may emerge, shared by a population of agents and with properties that may be hoped to parallel those of human language (Baronchelli et al., 2009; Gong, 2009; Smith, 2014; Smith et al., 2003).

Reducing the human population to a collection of artificial agents obeying some simple rules certainly raises some concern, but such an approach may indeed be legitimate. The reason is that in some respects humans behave in a surprisingly regular manner, as demonstrated by their mobility patterns (González et al., 2008), epidemic spreading (Pastor-Satorras and Vespignani, 2001), car traffic dynamics (Chandler et al., 1958), and also language formation (Jaeger et al., 2009). The advantage of dealing with a collection of (communicating) agents is that one can use the methodology developed in the physical sciences to investigate systems composed of many (interacting) atoms, such as gases, liquids or solids. Recent years have seen particularly numerous attempts to apply concepts and tools developed in the investigation of physical systems to the study of collective phenomena emerging in social structures (Castellano et al., 2009).

Simple rules followed by agents are designed to mimic some aspects of human interactions. One should take into account, however, that such interactions are typically quite complex and encompass, in addition to verbal communication, also gestures, feedback, pointing, or correction of mistakes. This complexity may be disentangled into so-called discourse frames (Goffman, 1974). In multi-agent modelling, one typically focuses on a particular discourse frame, which is implemented with a specific goal, such as drawing attention to some object in the world or getting the listener to perform a particular action. Such an implementation abstract and mimic interactions of communicating individuals and is usually called a language game (Wittgenstein, 2009).

A number of language game models have been studied in some detail, including guessing games, description games and construction games (Cangelosi and Parisi, 2002; De Beule et al., 2006; Lyon et al., 2007). The games are played repeatedly, each time between only two agents, and thus solely at the local level. As a result, however, certain common linguistic conventions disseminate throughout the population. Therefore, within such an approach, one can study the process of self-organization of communication, as a result of which a global linguistic coherence emerges in the population (e.g., a common set of sounds, words, categories or syntactic structures). One can also formulate conditions needed for the emergence of such a coherence as well as analyse its structure and possible further evolution. Such multi-agent modelling can be highly versatile and enables us to take into account, for example, phylogenetic evolution of essential traits, ontogenetic language learning, cultural (horizontal and/or vertical) language transmission, the structure of the network of social interactions, agents' mobility, and many other factors.

An important class of language games, which can be used to model such semiotic dynamics and the cultural formation and evolution of language, is the naming game (Steels, 1995). This game was conceived to explore the role of self-organization in the evolution of language, but due to its numerous versions and extensions, it acquired a paradigmatic role in the field of semiotic dynamics. The original paper (Steels, 1995) mainly focused on the formation of a vocabulary as a mapping between words and meanings (e.g., names for objects). It evolves through successive interactions, i.e., events that involve a certain number of agents (two, in most implementations) and meanings. Each agent develops its own vocabulary, trying to maximize communication success. This results, however, in the alignment of their vocabularies. Thus, a globally shared vocabulary emerges as a result of local adjustments of individual word–meaning associations. In Section 2, we provide a more detailed description of the naming game and briefly mention some related models.

In Section 3, we consider the use of language games as an approach to semiotic dynamics. These games resemble the so-called signaling game that was proposed by D. K. Lewis over 50 years ago, in a philosophical rather than a linguistic context (Lewis, 1969). In later, more language-oriented models based on Lewis' signaling games, a common approach is to apply agents which try to establish an unambiguous language using reinforcement learning to generate and recognize signals (Bachwerk, 2011; Barrett, 2006; Barrett, 2009; Franke, 2016; Mühlenbernd and Franke, 2012b; Skyrms, 2002; Van Eecke and Beuls, 2020). In some cases, however, they work out a language which is not fully effective and contains homonyms or synonyms. Certainly, the actions of agents in language games with reinforcement learning can be more sophisticated, and some of the research conducted along these lines has a strong cognitive flavour.

There is a widespread belief that the formation of modern languages was preceded by an intermediate, less complex stage, the so-called protolanguage. Despite intensive research, the structure, function, and modality of protolanguage largely remain a mystery (Zywiczynski et al., 2017). Following Bickerton (1996, p. 51), by protolanguage we mean a lexicon without syntax, and we are mainly interested in the processes of its formation and coordination within a population. Such linguistic synchronization that can spontaneously take place in a population of communicating individuals, and the emergence of single-word communication, may certainly be relevant to modelling some aspects of protolanguage formation. However, the nature of this kind of research is such that we do not refer to any species, nor do we use any kind of timescales or dating. We can only speculate that our studies refer to the earliest stages of (lexical) protolanguage formation. At such a stage, however, "words" and "meanings" were still *in statu nascendi*, and the usage and interpretation of such concepts in our models should be considered with some care. Language games might also contribute to the debate about the nature of protolanguage, and we address this issue in Section 4. Of particular interest is the problem of whether protolanguage was holistic (Wray, 1998), compositional (Bickerton, 1990), or maybe a more complex scenario led to its emergence (Smith, 2006; Jackendoff, 2002). Various language game models address the formation of compositional language (Kirby and Hurford, 2002; Franke, 2016; Steinert-Threlkeld, 2020), and there have been some attempts to set the emergence of protolanguage in a broader context of language formation and subsequent evolution (Steels, 2005).

The advantage of multi-agent modelling is its flexibility. We can easily equip agents with various additional features, which are not necessarily related to their linguistic performance. When analysing language formation processes, one should also consider such features, as language is intricately interrelated with other parts of our activity. However, if we were to take into account all kinds of social interactions along with economic status, political situation and perhaps other factors (Trudgill, 2000), we would develop a quite unmanageable model. Thus, it is probably necessary to restrict ourselves to some simpler analysis. In Section 5, we will analyse how the mobility of agents affects the dynamics of the language games they play. As we will show, even this single factor may considerably affect language formation.

In our review, we focus on very simple communication between agents, mainly on single-word communication, referring only very briefly to higher-level language structures. Consequently, the term "language" as used in our review refers rather to a mapping between forms and meanings. Moreover, in what follows we refer to forms and utterances as "words", as is common in the literature on language games. In some places, we draw attention to similarities between language formation and certain more general processes in multi-agent or physical systems, such as self-organization, symmetry breaking, or surface-tension-driven dynamics. Conclusions and some final remarks are given in Section 6.

2. LINGUISTIC SYNCHRONIZATION IN THE NAMING GAME

The primary motivation for introducing the naming game was to show that communicating agents, without any central control or steering, can spontaneously bootstrap and synchronize a linguistic convention finally shared by the entire population (Steels, 1995). Many different versions of the naming game have already been examined, for example, Baronchelli (2011), Bleys et al. (2009), Filho et al. (2009), De Vylder and Tuyls (2006), Gao et al. (2014), Li et al. (2013), Lorkiewicz and Katarzyniak (2014), Lou et al. (2018), Maity et al. (2013), Stadler et al. (2012), Steels and McIntyre (1998), Tria et al. (2012), Wellens and Loetzsch (2012), Zhou et al. (2018), to mention just a few. Here, we present the naming game in its elementary form to illustrate its dynamics. In this version, called the minimal naming game (Baronchelli et al., 2006), agents are engaged in pairwise interactions trying to establish a name of a given object. Each agent is equipped with an inventory, where the words that are in use are stored. Initially, all inventories are empty. At each time step, a pair of interacting agents is randomly chosen, one playing as "speaker" and the other as "hearer", and they communicate according to the following rules:

- The speaker randomly selects one of its words (or invents a new word if its inventory is empty) and conveys it to the hearer;
- If the hearer's inventory contains this word, the two agents update their inventories so as to retain only the word that was communicated (success);
- Otherwise, the hearer adds the word to those already stored in its inventory (failure).

These rules are illustrated in Fig. 1.

Initially, one observes some accumulation of words in agents' inventories, and due to the random selection of words by speakers, the communication seems to be quite disordered and inefficient. After some time, however, a global consensus is reached and all agents end up with only one and the same word in their repositories. All subsequent communication attempts are, of course, successful. In the naming game, one can measure the level of consensus among agents using a communicative success rate, defined as the proportion of successful communication attempts (Steels, 2015). In fact, to complete the definition of the model, one has to specify a network of interactions, the edges of which determine which pairs of agents may communicate. Several networks have been examined, including complete graphs (Baronchelli et al., 2006), regular two-dimensional lattices (Baronchelli et al., 2006; Lu et al., 2008), small worlds (Dall'Asta et al., 2006; Liu et al., 2009), complex networks (Dall'Asta et al., 2006) and directed networks (Lipowski et al., 2017), and in all cases a global consensus was reached, albeit the time needed to reach such a state is network-

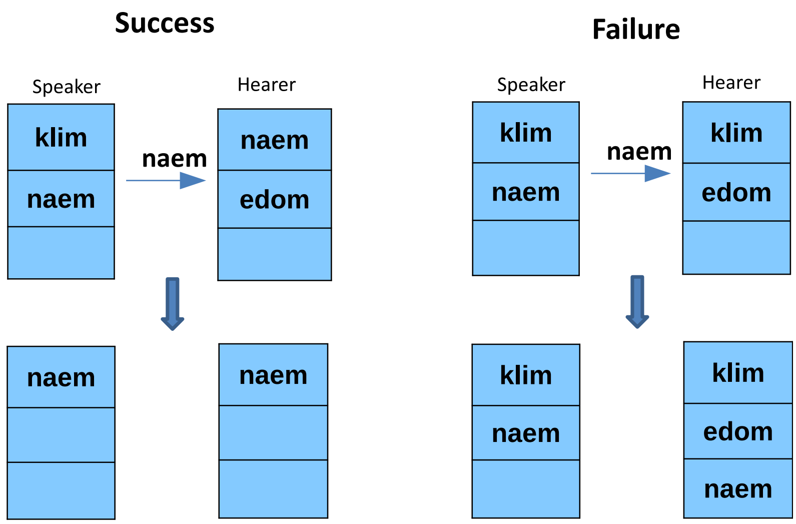

Fig. 1. An elementary step in the single-object version of the naming game.

dependent. It is only in networks with a strong community structure that a global consensus may not be reached and the system remains in a multi-language regime (Dall'Asta et al., 2006). Such a clustering of agents may also be induced dynamically in models using adaptive weighted networks (Lipowska and Lipowski, 2012).

As defined above, success in the minimal naming game completely erases all words but the successful one. In some other versions of the naming game, less severe inhibition of unsuccessful words can be implemented by means of weights (Steels and McIntyre, 1998). Such a mechanism may correspond to some degree of memory loss by the communicating individuals, which seems to be an essential ingredient of efficient communication systems. We will return to this point in Section 6.

Research on the naming game is focused mainly on the formation of a vocabulary, i.e., a set of associations between words and meanings (for instance, objects), but related models have also been used to examine the formation of linguistic categories. Such structures fundamentally determine our perception, recognition and understanding of the surrounding reality. Probably the best-researched example of linguistic categories is colour, as, with amazing universality, in virtually all languages an essentially infinite multitude of hues is classified into several colours (Lindsey and Brown, 2006; Saunders and van Brakel, 1997; Zaslavsky et al., 2020; Zaslavsky et al., 2019). Due to progress in the cognitive sciences, a certain mechanism of the creation of categories emerges, according to which they are culture-dependent conventions shared by a given group. There are several studies analysing computer models in which linguistic categories emerge (Baronchelli et al., 2010; Komarova et al., 2007; Li et al., 2017; Loreto et al., 2012; Puglisi et al., 2008), and a satisfactory agreement with empirical data (Cook et al., 2005) can be achieved in some cases.

Interesting implementations of the naming game have also been made in systems of embodied artificial agents (robots) (Steels and Loetzsch, 2012; Steels, 2015). Various aspects of the dynamics of the naming game have already been examined, such as the finite memory of agents (Wang et al., 2007), their reputation (Brigatti, 2008), preference in communication for agents with richer inventories (Lipowska and Lipowski, 2014), or the inclination to use a word shared by the majority of agents (Lei et al., 2010). A version of the naming game coupled with genetic evolution of a certain trait of agents leads to an interesting bio-linguistic transition, which is possibly a manifestation of the so-called Baldwin effect (Lipowski and Lipowska, 2008). The Baldwin effect provides a Darwinian explanation of the genetic fixing of traits that are learned or developed during the lifespan (Baldwin, 1896). Pinker and Bloom (1990) used the Baldwin effect as an argument for an explanation of the origins of language and the evolution of a Language Acquisition Device. Deacon (1997), on the other hand, claimed that Baldwinian inheritance can affect only general cognitive capabilities underlying language acquisition. Simulations by Munroe and Cangelosi (2002) support Deacon's hypothesis. Likewise, Christiansen et al. (2006) suggest that the influence of the Baldwin effect on language formation is most likely restricted only to its functional features that improve communication abilities. Also in the model of Lipowski and Lipowska (2008), the genetically evolving trait is a certain language learning ability, which may be interpreted as a functional trait.

We should also mention that the naming game may be used to reproduce some experimental results on the spontaneous emergence of social conventions (Centola and Baronchelli, 2015), to detect community structure in complex networks (Lu et al., 2009; Zhang and Lim, 2010), or to provide a broadcasting protocol in sensor networks (Lu et al., 2006; Lu et al., 2008). Some review articles on the naming game, which focus on its statistical-mechanics properties (Baronchelli, 2016), provide an in-depth discussion of the emergence of a common lexicon and of a shared set of linguistic categories (Loreto et al., 2011), or analyse a Bayesian learning framework and provide an extensive bibliography (Marchetti et al., 2020), are also available.

3. SIGNALING GAME AND REINFORCEMENT LEARNING

Of course, it would be desirable to study agents that are able to form a language somewhat more complex than a name of a single object. A natural extension is thus establishing names for several objects. In principle, one can define a multi-object naming game, where agents use some non-verbal actions (like pointing) to decide which object they are talking about and whether a communication attempt was successful or not. Basically, this means that agents would negotiate names for each object independently, and the situation would not be much different from the single-object version analysed in the previous section (Baronchelli et al., 2006). It is more interesting and ambitious to assume that agents can recognize the communicated signal (word) and take an appropriate action (e.g., choose an object corresponding to the word). The pioneering work along these lines by Lewis (1969) laid the ground for an important class of models implementing what is known as a signaling game, which has found numerous applications in economics, evolutionary biology, and also linguistics (Skyrms, 2010). Although the signaling game requires agents with more sophisticated cognitive abilities than those in the naming game, it can be used to model very low-level types of learning and cognition, such as the signaling behaviour of some type of bacteria (Skyrms, 2010; Fiegna and Velicer, 2003). Most likely, higher-level learning skills are needed to reproduce the emergence of more complex phenomena in human language, such as compositionality or grammar.

In the signaling game, a correct/incorrect recognition of the object should result in some payoff/penalty, which accumulates in the form of weights corresponding to signals or actions (e.g., chosen words or objects). In this way, agents learn over time which actions are likely to be successful.

The signaling game has been typically studied within a class of learning rules known as reinforcement learning, which this paper will address exclusively. However, it should be mentioned that the signaling game has also been studied with a range of other classes of update rules, for example, replicator dynamics (Skyrms, 2010) or imitation dynamics (Zollman, 2005).

In multi-agent formulations of the signaling game, agents play in turn the role of a speaker or hearer. A speaker learns which word has the best match with a given (selected) object, say O, and a hearer tries to find the best matching object when a given word, say W, is communicated by a speaker. When the object indicated by the hearer is the same as that chosen by the speaker, they achieve a communicative success. As a reward, the speaker and the hearer

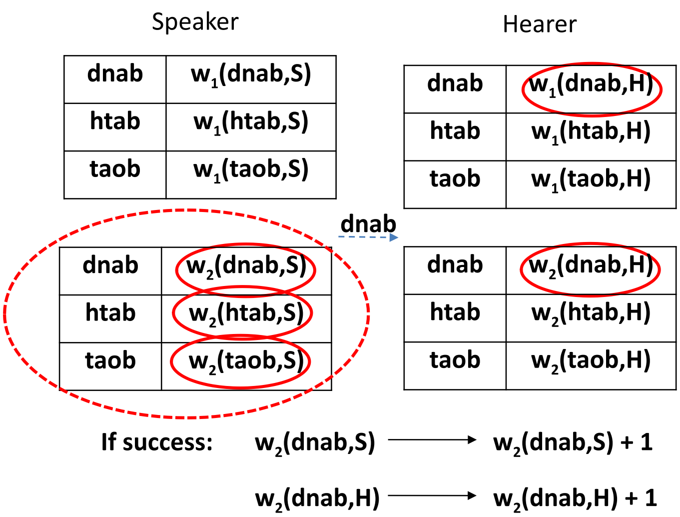

Fig. 2. An elementary step in a 2-object version of the signaling game model with reinforcement learning (Lipowska and Lipowski, 2018). The speaker randomly chooses an object (the corresponding section of the inventory is encircled by a dotted line). Using the relevant weights (in solid circles), the speaker selects one of its words (here: “dnab”). Next the hearer tries to guess the object the speaker is talking about, taking into account the weights of the communicated word (in circles). If the hearer’s guess is correct, both agents increase their corresponding weights by 1. Otherwise, the weights remain unchanged.

increase the weights of W (in association with O). Further successful communication with the pair $W-O$ (which continues to increase its weight) can effectively lock the agents on this pair; namely, whenever they want to talk about O they will use the word W. Provided that for other objects agents also establish similar unique associations (different words for different objects), they will be able to communicate effectively about their world, i.e., a collection of objects.

This will not necessarily happen, however. It may be that a certain word will be associated with two (or more) objects or a certain object with two (or more) words. Such homonyms and synonyms break the unique object–word mapping and usually reduce the efficiency of communication. However, they are by no means undesirable or unrealistic, since all natural languages contain such forms. Let us also note, though, that true synonyms are considered to be non-existent or at least very rare compared with homonyms (Clark, 1995; Goldberg, 1995; Lyons, 1981). We should also mention that there are some studies which focus on conditions that support the emergence of ambiguity in signaling games (Santana, 2014). Moreover, ambiguous signaling does not necessarily reduce communication efficiency (Mühlenbernd, 2021; O'Connor, 2015), as can be deduced from the principles of mutual information maximization and word entropy minimization (Ferrer-i-Cancho, 2005).

Efficiency in the signaling game can be measured by the mean Shannon information content of each signal (Barrett, 2006), but for our considerations it is sufficient to define it as in the naming game, namely as the proportion of successful communication attempts (see Fig. 2). It should be emphasized, however, that the very notion of language efficiency constitutes a multidimensional problem that should be examined from various perspectives, and perhaps a more general approach than a typical linguistic one would be needed to obtain a comprehensive understanding of it (Semple et al., 2022). For example, tolerance of homonyms and the rareness of synonyms result from certain conflicting forces and constraints which seem to govern language formation processes, and which can be inferred from the principle of mutual information maximization (Ferrer-i-Cancho and Vitevitch, 2018). Such an approach can also be applied to the study of word order (Ferrer-i-Cancho, 2017). Such an information maximization principle has also been implemented in some multi-agent language games, and under a certain regime, Zipf's law - which describes the frequency of word usage - was reproduced (Urbina and Vera, 2019; Vera et al., 2021).

An adaptation of the signaling game that focuses on language evolution was proposed by Lenaerts et al. (2005). They analysed not only the emergence of language and efficiency of communication, but also the intergenerational transmission of language. Namely, they divided the population of agents into teachers and pupils, and examined how the pupils acquired the teachers' language and whether such a language enabled the pupils to communicate effectively with each other.

Recently, we have analysed a similar model (its rules are illustrated in Fig. 2) but with the main emphasis on the global aspects of the dynamics (Lipowska and Lipowski, 2018). Let us note that in our model, the agents use only one set of weights, albeit in different ways, to determine a word (when they are playing as sender) or an object (as hearer). A sender takes into account the weights of all words in the inventory corresponding to the chosen object. On the other hand, to interpret a communicated word, the hearer takes into account the weights of that word in all inventories (see Fig. 2). It should be mentioned, however, that in some implementations of the signaling game, separate inventories are used for the selection of communicated words and for their interpretation (Skyrms, 2010; Mühlenbernd, 2014).

A typical feature of reinforcement learning systems is that the accumulation of weights teaches agents which actions are likely to be optimal, but at the same time it may lead to some deadlock configurations, where agents are stuck in a language that is far from being efficient, yet can no longer be changed. A possible solution - not unrealistic in fact - is to introduce a process of population renewal, in which old (and thus overtrained) agents are replaced with young (and therefore linguistically very flexible) ones. Alternatively, one can introduce certain forms of lateral inhibition, which reduce the weights of competing words (Spike et al., 2017).

It turns out that it is much easier to generate an efficient language in signaling games with population renewal or lateral inhibition. What is more, the dynamics of language evolution in these cases exhibit some similarity to the naming game, and this is because both models generate what is called surface tension. Interestingly, there are some linguistic data analyses that suggest that the dynamics of real languages also appear to be driven by surface tension (Burridge, 2017; Burridge and Blaxter, 2020). We will return to this point in Section 5.

Let us emphasize, however, that despite some similarities, the naming game and the signaling game are very different. In contrast to the signaling game, in the naming game there is no need for the hearer to interpret the communicated signal. Instead, before communicating the word, the speaker draws the attention of the hearer to the selected object, for example using pointing or gestures. Even multi-object versions of the naming game can operate according to such rules (Steels and McIntyre, 1998).

Certain versions of the signaling game focus on the role of spatial and network structures (Mühlenbernd, 2011; Mühlenbernd and Franke, 2012a; Mühlenbernd and Nick, 2014; Wagner, 2009; Zollman, 2005). Moreover, some studies combine (reinforcement) signaling games with network formation processes (Huttegger et al., 2014; Skyrms, 2010, ch. 14). Especially in the context of language evolution, simulations of the signaling game are typically constructed with many agents. It is interesting, however, to examine even a two-agent version (Lipowski and Lipowska, 2009). In this case, the emergent language also contains homonyms and synonyms. What is more, homonyms turn out to be much more stable than synonyms, which is in agreement with some linguistic observations and evolutionary modelling reported by Hurford (2003).

An interesting model, which combines the naming game with learning based on Bayesian inference, was proposed by Patriarca et al. (2020b). In their model, agents learn to associate different objects with two possible names, and the main emphasis is on the cognitive process rather than on the semiotic dynamics. Bayesian inference is at the core of numerous approaches which emphasize the role of the context of speech and reasoning, for example, the rational speech act model (Goodman and Frank, 2016). There are also some studies that identify inferential communication as the crucial prerequisite that allowed language to emerge (Scott-Phillips, 2015).

The above brief description of several linguistic versions of the signaling game is rather general, and omits some details (such as learning strategies, the weight increases or decreases, and the network of interactions) as well as the parameters of the model (number of agents, number of objects, number of words). All these factors play an important role and influence the behaviour of the model; of course, they are discussed in more detail in the literature (Lenaerts et al., 2005; Lipowska and Lipowski, 2018; Lipowski and Lipowska, 2009; Skyrms, 2010).

4. LANGUAGE GAMES AND THE NATURE OF PROTOLANGUAGE

If language expressions cannot be segmented into parts whose meanings make up the meaning of the whole expression, the language is called holistic. However, usually the meaning of an expression is a function of the meanings of its components and the way in which they are combined. This feature, shared by virtually every language, is called compositionality (Brighton, 2002, p. 29; Gong and Wang, 2005, p. 7; Hurford, 2012, pp. 621-623; Krifka, 2001). The formation of a compositional language can be analysed within an iterated learning model (Kirby and Hurford, 2002), which is based on the vertical transmission of language (master–student) rather than on horizontal transmission (as in the naming game). The emergence of a compositional language has been reported in a multi-agent system without a strict vertical transmission but within a population of communicating agents that interact with the environment (Mordatch and Abbeel, 2018), and also in some versions of the signaling game (Franke, 2016; Skyrms, 2010, ch. 12; Steinert-Threlkeld, 2016; Steinert-Threlkeld, 2020). A simple mechanism demonstrating the emergence of a compositional language is based on re-use (De Beule and Bergen, 2006; Vogt, 2005). In this approach, when an agent needs to convey a new meaning, it tries to invent a new word or a combination of words based on its repertoire of holistic words/signals. The re-use mechanism may suggest the gradual formation of protolanguage (and then languages) largely in line with the hypotheses of some researchers (Steels, 2005).

Such studies can certainly contribute to the debate concerning the nature of protolanguage. The synthetic nature of protolanguage was advocated by Bickerton (1990), Bickerton (2000), Bickerton (2007), who claimed that protolanguage had incorporated symbols conveying atomic meanings, which could have been used together in ad hoc sequences. Then, language developed through the synthesis of such proto-words into more and more complex, hierarchically structured utterances. An opposing explanation was presented by Wray (1998), Wray (2000), who suggested a holistic nature of protolanguage, which “had no words and no rules, just utterances associated with specific meanings, that achieved [certain] goals” (Wray and Perkins, 2000, p. 14). The transition to language took place through a process of analysis, in which holistic utterances were gradually broken down into words and their combinations. Smith (2006) in turn suggested an account unifying these two apparently opposing theories. Namely, he accepted the possibility that basic words (nouns, verbs) were formed as a result of an analysis process from an originally holistic protolanguage, and then the resulting synthetic protolanguage underwent processes such as grammaticalization and developed into language. A natural further step would be to assume that protolanguage could have covered a whole series of stages, not just two (Jackendoff, 2002). Moreover, such stages were not strictly segregated, perhaps, as different processes could have overlapped and intermingled, with multiple linguistic features being at different stages of development. Obviously, such complex and interacting processes are too difficult to capture by computer modelling, but we can at least try to reconstruct their characteristic phases. It appears that the naming game and the signaling game are well suited to testing hypotheses on the nature of protolanguage, and may offer some valuable insight into this fundamental problem.

5. LANGUAGE EVOLUTION AND MOBILITY

Language, as one of our human attributes, is interrelated with many other parts of our activity. Social interactions, economic status or political situation influence the way language is acquired and changed, or sometimes falls into oblivion. Language, as an integral part of our culture and way of life, is also intricately related to migrations of people

(Canagarajah, 2017; Williams, 1988). Various tribes, ethnic groups, or even entire nations have permanently settled certain areas, while some others, for various reasons, almost constantly migrate. Migration can both mix and separate human communities, and language formation processes should thus be strongly influenced by such a factor. Moreover, some modern trends, especially globalization, most likely increase human migration (Czaika and de Haas, 2014). Some research even suggests that in some areas the merging of multinational and multicultural migrants creates a new kind of *super-diverse* societies, and to describe their intercommunication, languages as traditionally understood do not seem to be sufficient (Jørgensen et al., 2011).

Thus, it would be desirable to have some general understanding of how migration affects language formation processes, and perhaps vice versa. As a simple model enabling such an investigation, we can employ a suitably extended naming game. Recently, we analysed such a model in which agents occupy sites in a lattice and can play the naming game with neighbouring agents, but with some probability they may also migrate around that lattice (where a fraction of the sites is empty) (Lipowska and Lipowski, 2017). Taking into account that people's willingness or need to migrate may depend on their language or culture, the probability of an agent's migrating also depends on the language it uses. One of our findings was not entirely obvious, namely, that languages associated with a lower probability of migration turned out to be favoured by the model dynamics and eventually came to prevail in the system. Let us note that in the naming game without migration, languages are perfectly equivalent, and the (dynamic) adoption of the language used by the agents when they reach linguistic synchronization is purely random. Apparently, language-specific migration breaks this symmetry, with low-migration languages being favoured.

Our model may suggest, then, that the languages of settlers might be favoured over the languages of nomadic communities. Of course, we are aware that our model is far too simple to explain the complexity of language competition, which is a process affected by a number of linguistic as well as non-linguistic factors (Joseph et al., 2003; Patriarca et al., 2020a).

We also analysed some global aspects of the naming game with migration (Lipowska and Lipowski, 2021). In particular, we examined how the length of borders between different languages shrinks in time. Such shrinking might be induced by the so-called surface tension, which in the linguistic context may be interpreted as a tendency to conform with the majority of our neighbours when adopting a new language. The relatively fast shrinking that we observed in our simulations indicates that the dynamics of such systems do generate surface tension. Such results, showing that the surface tension drives some models of language formation, are consistent with some recent empirical analyses by Burridge (2018) and Burridge and Blaxter (2020). Investigating the Survey of English Dialects (Orton and Dieth, 1962), they found some indications that surface tension seems to shape patterns of English dialect changes. It would certainly be desirable to examine how robust is the mechanism that generates the surface tension in language evolution models. Some other studies have also shown that the migration of agents has a considerable influence on the reaching of consensus (Baronchelli and Pastor-Satorras, 2009). The emergence of consensus has also been analysed in a population of agents moving in a continuous space (Baronchelli and Diaz-Guilera, 2012) and in robotic swarms (Cambier et al., 2017).

6. CONCLUSIONS AND FINAL REMARKS

This paper has discussed some of the issues that arise when analysing a population of agents which try to establish a shared communication system, preferably with characteristics similar to those of human language. Hopefully, we have managed to demonstrate that multi-agent modelling offers a valuable computational tool with which to approach such problems. Our presentation is certainly focused on issues in this field with which we have already gained some experience and which we believe are important and stimulating. In particular, we have presented mainly sociocultural approaches, where the selection of a given word or a structure is based on cultural choice and its adoption by others. An important class of models, hardly discussed in our review, emphasizes the sociobiological aspects of language formation. Such approaches often refer to the notion of fitness, and aim to explain the development of some innate (e.g., cognitive, neural, vocal) language-related predispositions (Hurford, 1989; Nowak et al., 2000). Some multi-agent models of the emergence of language may also be considered as a mixture of sociobiological and sociocultural approaches Lipowski and Lipowska (2008). We have also omitted several papers where multi-agent simulations are used to show that statistical learning provides an efficient means of language acquisition (Christiansen et al., 2000; Christiansen and Curtin, 1999). Moreover, although we briefly mentioned the iterated learning framework, which originated from modelling studies, we did not discuss how widely it is currently used in experimental research into iterative learning of artificial languages by human participants (Kirby et al., 2008; Kirby et al., 2014).

The problem of language emergence and evolution is of interest to researchers from a number of disciplines, including evolutionary game theory (Nowak and Krakauer, 1999; Skyrms, 2010), artificial life (Steels and Loetzsch, 2012), cognitive science (Barr, 2004; Goodman and Frank, 2016), and evolutionary linguistics (Oliphant, 1996; Smith, 2002). More efforts to confront these different strands of research and develop a unified approach are certainly desirable and are frequently undertaken. For example, an attempt to compare several approaches in which language as a learned signaling system may emerge was made by Spike et al. (2017). They suggest that there are three requirements for the emergence of language, namely (i) referential information (e.g., pointing), (ii) the presence of a bias against ambiguity (e.g., using homonyms does not always result in successful communication, so their usage in the signaling game is effectively punished), and (iii) some form of information loss (e.g., forgetting due to the limited memory of agents or population renewal). The signaling game implements the above requirements to some extent, but more sophisticated strategies are also feasible Spike et al. (2017). This type of meta-analysis of various approaches is certainly valuable for directing some future research in this field. It seems that certain stages in the evolution of language can be distinguished, determined by particular qualitative changes or new developments (Jackendoff, 1999; Steels, 2005). Vocabulary formation, modelled by means of the naming and signaling games (Baronchelli et al., 2006; Barrett, 2006; Ke et al., 2002; Tria et al., 2012), was one of the earliest stages, and was most likely followed by the formation of regularity and compositionality (Brighton, 2002; De Beule and Bergen, 2006; Gong, 2009; Gong, 2011), and finally that of syntax generating hierarchical structures (Frank et al., 2012; Steels, 2011). Modelling these latter stages is certainly more difficult, but there are some indications that even here progress is likely to be made (Becerra-Bonache and Jiménez-López, 2015; Beuls and Steels, 2013; Cuskley et al., 2017; Garcia-Casademont, 2017; Gong, 2011; Jaeger et al., 2009; Kirby and Hurford, 2002; Kirby et al., 2014; Kirby et al., 2015; Mordatch and Abbeel, 2018; Steels, 2016; Steels and Szathmáry, 2018).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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