Experiments on the Acquisition of Cognitive and Linguistic Competence to Communicate Propositional Logic Sentences

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Abstract

We describe some experiments which simulate a grounded approach to the acquisition of the cognitive and linguistic competence required to communicate propositional logic sentences. This encompasses both the construction of a conceptualisation of its environment by each individual agent and of a shared language by the population. The processes of conceptualisation and language acquisition in each individual agent are based on general purpose cognitive capacities, such as categorisation, discrimination, invention, adoption and induction. The construction of a shared language by the population is achieved using a particular type of linguistic interaction, known as the evaluation game, which gives rise to a common set of linguistic conventions through a process of self-organisation.

This work addresses the problem of the acquisition of both the semantics and the syntax of propositional logic. Trying to learn these two aspects at the same time is more difficult than learning the semantics or the syntax of propositional logic separately. Because the agents must coordinate their linguistic behaviour taking into account only the subset of objects which constitutes the topic of a particular linguistic interaction. This means that a pair of agents can communicate successfully about a particular subset of objects (a topic) even if they use different conceptualisations (formulas) in order to identify the same topic. And this introduces a high degree of ambiguity in the interpretation process the agents have to deal with when they try to construct a shared communication language. In spite of this, the results of the experiments show that at the end of the simulation runs the individual agents build different conceptualisations and grammars, but that the conceptualisations and grammars of the agents in the population are compatible in the sense that they guarantee the unambiguous communication of propositional logic sentences.

Introduction

This paper addresses the problem of the acquisition of both the semantics and the syntax (i.e., lexicon and grammatical constructions) required for constructing and communicating concepts of the same complexity as propositional logic formulas. It describes some experiments in which a popula-

tion of autonomous agents without prior linguistic knowledge constructs at the same time a conceptualisation of its environment and a shared language.

The research presented in this paper builds up on previous work on the acquisition of the semantics of logical connectives (Sierra 2002) by addressing the problem of the acquisition of both the semantics and the syntax of propositional logic. In (Sierra 2002) a grounded approach to the acquisition of logical categories (i.e., the semantics of logical connectives) based on the discrimination of a "subset of objects" from the rest of the objects in a given context is described. Logical categories are constructed by the agents identifying subsets of the range of the truth evaluation process (i.e., sets of Boolean pairs or Boolean values) which result from evaluating a pair of perceptually grounded categories or a single category on a subset of objects. Discrimination is performed characterising a "subset of objects" by a logical formula constructed from perceptually grounded categories which is satisfied by the objects in the subset and not satisfied by the rest of the objects in the context.

The associated problem of the acquisition of the syntax of propositional logic by a population of autonomous agents without prior linguistic knowledge has been addressed independently as well. In (Sierra and Santibáñez 2007) an approach to the acquisition of the syntax of propositional logic based on general purpose cognitive capacities, such as invention, adoption and induction, and on self-organisation principles is proposed. The experiments described in (Sierra and Santibáñez 2007) show that a shared language (i.e., a lexicon and a grammar) expressive enough to allow the communication of meanings of the same complexity as propositional logic formulas can emerge in a population of autonomous agents without prior linguistic knowledge. The acquisition of the syntax of subsets of logic has been addressed as well by other authors. In particular (Steels 1998; Batali 2002; Kirby 2002) study the emergence of casebased and recursive communication systems in populations of agents without prior linguistic knowledge. However none of these works deals with the problem of the acquisition of both the semantics and the syntax of logic.

The experiments described in this paper extend therefore previous work by using a linguistic interaction (the evaluation game) in which the agents must first conceptualise the topic (a subset of objects) using the mechanisms pro-

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posed in (Sierra 2002) for the acquisition of logical categories, and then construct a *shared language* (a lexicon and a grammar) using the invention, adoption, induction and self-organisation mechanisms proposed in (Sierra and Santibáñez 2007).

The rest of the paper is organised as follows. Firstly we describe the mechanisms the agents use in order to conceptualise sensory information. Secondly we consider the process of truth evaluation and explain how logical categories can be discovered by identifying sets of outcomes of the truth evaluation process. Then we focus on the construction and emergence of a shared communication language describing the main steps of *the evaluation game:* conceptualisation, generation, interpretation, induction and co-adaptation. Next we present the results of some experiments in which three agents without prior linguistic knowledge build a conceptualisation and a shared language that allows them to construct and communicate meanings of the same complexity as propositional logic formulas. Finally we summarise the main ideas we try to put forward in this paper.

Conceptualising Sensory Information

In this section we describe how the agents conceptualise the sensory information they obtain capturing images of the white board with their cameras, in order to characterise subsets of objects pasted on it. We assume an experimental setting similar to that proposed in *The Talking Heads Experiment* (Steels 1999): A set of robotic agents playing language games with each other about scenes perceived through their cameras on a white board in front of them. Figure 1 shows a typical configuration of the white board with several geometric figures pasted on it.

In the conceptualisation part of a language game the agents capture an image of an area of the white board with their cameras, segment that image into coherent units in order to identify the objects which constitute the context of the language game, and they use some *sensory channels* to gather information about each segment. In particular, in the experiments described in this paper the agents use three **sensory channels**: (1) H(o), which computes the horizontal position of an object o; (2) V(o), which computes its vertical position; and (3) L(o), which computes its light intensity. The values returned by these sensory channels are scaled so that its range is the interval (0.0 1.0).

The data returned by the sensory channels are values from a continuous domain. To be the basis of a natural language conceptualisation, these values must be transformed into a discrete domain. In the experiments categorisation is performed dividing up the domain of output values of a particular sensory channel into regions and assigning a **category** to each region (Steels 1999). For example, the range of the V channel can be cut into two halves leading to the categories [down] (0.0 < V(x) < 0.5) and [up] (0.5 < V(x) < 1.0). Object 3 in figure 1 has the value V(O3)=0.2 and can therefore be categorised as [down].

As the agents build categories in order to conceptualise sensory information they construct as well cognitive procedures, called **categorisers**, which allow them to check whether these categories hold or not for a given object.

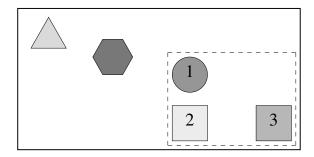


Figure 1: The area of the white board captured by the agents cameras (the context of the game) is the lower right rectangle.

Categorisers give grounded meanings (Harnad 1990) to categories (symbolic representations) by establishing explicit connections between them and reality (external input processed by sensory channels). These connections are learned playing language games (Wittgenstein 1953; Steels 1999) and allow the agents to check whether a category holds or not for a given object. Most importantly they provide information on the sensory and cognitive processes an agent must go through in order to evaluate a given category.

The behaviour of the categorisers associated with the perceptually grounded categories used in the experiments presented in this paper can be described by linear constraints¹. For example, the behaviour of the categoriser associated with the category [left] can be described as follows: $[left]^C(x) \equiv 0.0 < H(x) < 0.5$.

Truth Evaluation: Logical Categories

We consider now the process of truth evaluation, and describe how logical categories can be constructed identifying subsets of the range of the truth evaluation process.

In this paper we consider **truth evaluation** as a cognitive process (denoted by E) capable of finding the categorisers of a tuple of categories, applying them to an object, and observing their output. If $\vec{c} = (c_1, \ldots, c_n)$ is a category tuple and o is an object, $E(\vec{c}, o)$ is a tuple of Boolean values (v_1, \ldots, v_n) , where each v_i is the result of applying e_i^C (the categoriser of e_i) to object e_i . For example, e_i^C (e_i^C), e_i^C), e_i^C (object 1 in figure 1) is neither on the lower part nor on the right part of the white board area captured by the agents' cameras.

The truth evaluation process can be applied to category tuples of any arity, but we only consider unary and binary category tuples. The range of the truth evaluation process for single categories is the set of Boolean values $\{0,1\}$, and its range for category pairs is the set of Boolean pairs $\{(0,0),(0,1),(1,0),(1,1)\}$. By considering all the subsets of these ranges the agents can represent all the Boolean functions of one and two arguments. The sixteen Boolean functions of

 $^{^{1}}$ We use the notation [cat] C to refer to the categoriser that is capable of determining whether category [cat] holds or not for a given object.

two arguments which can be constructed using this method are summarised in the following ten connectives in the internal representation of logical categories used by the agents: and, nand, or, nor, if, nif, oif, noif, iff and xor. Where and, or, if and iff have the standard interpretation $(\land, \lor, \to$ and \leftrightarrow), and the formulas (A nand B), (A nor B), (A nif B), (A oif B), (A noif B) and (A xor B) are equivalent to $\neg(A \land B)$, $\neg(A \lor B)$, $\neg(A \lor B)$, $\neg(A \to B)$, $(B \to A)$, $\neg(B \to A)$ and $\neg(A \leftrightarrow B)$, respectively.

The agents construct **logical categories** by identifying subsets of the range of the truth evaluation process. The *evaluation game* creates situations in which the agents discover such subsets and use them to distinguish a subset of objects from the rest of the objects in a given context². For example, the propositional formula up \leftrightarrow left characterises the subset of objects $T = \{O1, O3\}$, because it is true for all the objects in this subset and false for the rest of objects in the context. The result of evaluating the pair of categories (up, left) on subset T is the set of Boolean pairs $\{(1,1),(0,0)\}$. Formula up \leftrightarrow left is false for object O2, because the result of evaluating (up, left) on O2 is the Boolean pair $\{(1,1),(0,0)\}$.

The **categorisers of logical categories** are cognitive processes which allow determining whether a logical category holds or not for a tuple of categories and an object. The behaviour of the categorisers of logical categories can be described by constraints of the form $E(\vec{c},o) \in S_l$, where l is a logical category, S_l is the subset of the range of the truth evaluation process for which l holds, \vec{c} is a tuple of categories and o is an object. For example, the constraint $E((c1,c2),o) \in \{(1,1)\}$ describes the behaviour of the categoriser of the logical category [and] (i.e., $c1 \land c2$).

The truth evaluation process can be extended so that it can be applied to evaluate arbitrary propositional logic formulas using the categorisers of logical and perceptually grounded categories. The following is an inductive definition of the truth evaluation process E(A,o) for an arbitrary formula A of propositional logic and an object o:

- 1. If A is a perceptually grounded category [cat], then $E(A,o)=[cat]^C(o)$.
- 2. If A is a propositional formula³ of the form [l|F], where l is a logical category, F is a list of formulas and S_l is the subset of the range of the truth evaluation process for which l holds, then E(A,o)=1 if $E(F,o)\in S_l$, and 0 otherwise.

In this paper we call **intuitive reasoning** to a cognitive process which allows the agents to discover relationships that hold among the categorisers of perceptually grounded categories and logical categories. From a cognitive point of view it is very important, because it allows the agents to

perform some inference tasks which are at the basis of common sense knowledge and reasoning (McCarthy 1990). For example, using the categorisers of logical and perceptually grounded categories an agent can determine whether a given formula is a tautology (it is always true because of the meaning of its logical symbols) or an inconsistency (it is always false for the same reason). Similarly, it can discover that a given formula is a common sense axiom, i.e., it is always true because of the meaning of the perceptually grounded categories it involves. The formula $up \rightarrow \neg down$ is a good example of a common sense axiom. It is always true because the categoriser of down returns false for a given object whenever the categoriser of up returns true for the same object. The process of determining whether a formula is a tautology, an inconsistency or a common sense axiom by intuitive reasoning can be implemented using constraint satisfaction algorithms in this experiment, in general this can be done when the behaviour of the categorisers of perceptually grounded and logical categories can be described by constraints.

The Evaluation Game

The acquisition of linguistic knowledge by each individual agent and the emergence of a shared language in the population result from a process of self-organisation of a particular type of linguistic interaction, called the evaluation game, which takes place among the agents of the population. The main steps of *the evaluation game* (Sierra and Santibáñez 2007) can be summarised as follows.

1. Conceptualising the topic Firstly both agents, the speaker and the hearer, capture an image of the same area of the white board. The objects in that area constitute *the context* of the evaluation game. Then the speaker picks up a subset of objects from the context which will be *the topic* of the evaluation game. The rest of the objects in the context constitute *the background*.

The speaker tries to construct a *conceptualisation* of the topic, that is, a logical formula which is true for all the objects in the topic and false for all the objects in the background. It does so by finding a unary or binary tuple of categories such that its evaluation on the topic is different from its evaluation on any object in the background. Once it has found a discriminating category tuple, the speaker tries to find a logical category which is associated with the subset of Boolean values or Boolean pairs resulting from evaluating the topic on that category tuple, and constructs a conceptualisation of the topic applying this logical category to the discriminating category tuple.

In general an agent can build several concepts for the same topic. For example, if the context contains objects 1, 2 and 3 in figure 1, and the topic consists of objects 1 and 2, both formulas [iff, up, left] and [xor, up, right] can be used as conceptualisations of the topic.

2. Generating sentences The speaker generates sentences which express its conceptualisations of the topic. It tries to maximise the the probability of being understood by other agents by selecting the sentence with the highest score, and

²The representation of logical categories as subsets of Boolean tuples is equivalent to the *truth tables* used for defining the semantics of logical connectives.

³Notice that we use prefix, Lisp like, notation for representing propositional formulas: l is a logical category, F is a list of formulas and | is the standard list construction operator.

communicates that sentence to the hearer. The algorithm for computing the score of a sentence from the scores of the grammar rules used in its generation is explained in (Sierra and Santibáñez 2007).

The agents in the population start with an empty lexicon and grammar. Therefore they cannot generate sentences for most formulas at the early stages of a simulation run. In order to allow language to get off the ground, they are allowed to invent new sentences for those meanings they cannot express using their lexicon and grammar. As the agents play language games they learn associations between expressions and meanings, and induce linguistic knowledge from such associations in the form of grammar rules.

- 3. Interpreting the sentence If the hearer can parse the sentence communicated by the speaker using its lexicon and grammar, it extracts a formula (a meaning) and uses that formula to identify the topic. At the early stages of a simulation run the hearers cannot usually parse the sentences communicated by the speakers, since they have no prior linguistic knowledge. In this case the speaker points to the topic, and the hearer adopts an association between its conceptualisation of the topic and the sentence used by the speaker. Notice that the conceptualisations of speaker and hearer may be different, because different formulas can be used to conceptualise the same topic.
- **4. Co-Adaptation** Speaker and hearer check whether they referred to the same subset of objects. The evaluation game is successful if the hearer can parse the sentence communicated by the speaker, and its interpretation of that sentence identifies the topic (the subset of objects the speaker had in mind) correctly. Depending on the outcome of the evaluation game, speaker and hearer take different actions. We have explained some of them already (*invention* and *adoption*), but they also *adapt their grammars* to communicate more successfully in future games.

Coordination of the agents' grammars is necessary, because different agents can invent different expressions to refer to the same perceptually grounded or logical categories, and because the invention process uses random order to concatenate the expressions associated with the components of a given formula. In order to understand each other, the agents must use a common vocabulary and must order the constituents of compound sentences in sufficiently similar ways as to avoid ambiguous interpretations. The following self-organisation mechanisms are used to coordinate the agents' grammars (Steels 1999; Batali 2002).

We consider the case in which the speaker can generate a sentence and the hearer can parse it. If the speaker can generate several sentences for its conceptualisation of the topic, the sentence with the highest score is chosen for communication and the rest of the sentences are kept as *competing sentences*. Similarly if the hearer can obtain several formulas (meanings) for the sentence communicated by the speaker, the formula with the highest score is selected as its interpretation of the sentence and the rest of the formulas are kept as *competing meanings*.

If the topic identified by the hearer is the subset of objects the speaker had in mind, the evaluation game succeeds. The speaker increases the scores of the grammar rules it used for generating the sentence communicated to the hearer and decreases the scores of the grammar rules it used for generating competing sentences. The hearer increases the scores of the grammar rules it used for obtaining its interpretation of the sentence and decreases the scores of the rules it used for obtaining competing meanings. This way the grammar rules used successfully get reinforced, and the grammar rules used for generating competing sentences or competing meanings are inhibited.

If the topic identified by the hearer is different from the subset of objects the speaker had in mind, the evaluation game fails and both agents decrease the scores of the grammar rules they used for generating and interpreting the sentence used by the speaker, respectively. This way the grammar rules used without success are inhibited.

The scores of grammar rules are *updated* replacing the rule's original score S with the result of evaluating expression 1 (expression 2) if the score is *increased* (*decreased*).

$$minimum(1, S+0.1) \tag{1}$$

$$maximum(0, S - 0.1) \tag{2}$$

Induction of linguistic knowledge Besides inventing expressions and adopting associations between sentences and meanings, the agents use some *induction mechanisms* to extract generalisations from the grammar rules they have learnt so far. The induction mechanisms used in this paper are based on the rules of *simplification and chunk* in (Kirby 2002), although we have extended them so that they can be applied to grammar rules which have scores attached to them (Vogt 2005). The induction rules are applied whenever the agents invent or adopt a new association to avoid redundancy and increase generality in their grammars.

Instead of giving a formal definition of the induction rules used in the experiments, which can be found in (Sierra and Santibáñez 2007), we give an example of their application. We use *Definite Clause Grammar* for representing the internal grammars constructed by the individual agents. *Nonterminals* have two arguments attached to them. The first argument conveys semantic information and the second is a *score* in the interval [0, 1] which estimates the usefulness of the grammar rule in previous communication. Suppose an agent's grammar contains the following rules.

$$s(\text{light}, S) \rightarrow \text{clair}, \{S \text{ is } 0.70\}$$
 (3)

$$s(\text{right}, S) \rightarrow \text{droit}, \{S \text{ is } 0.25\}$$
 (4)

$$s([and, light, right], S) \rightarrow etclairdroit, \{S \ is \ 0.01\}$$
 (5)

$$s([or, light, right], S) \rightarrow ouclairdroit, \{S \text{ is } 0.01\}$$
 (6)

The induction rule of **simplification**, applied to 5 and 4, allows generalising grammar rule 5 replacing it with 7. In this case *simplification* assumes that the second argument of the logical category *and* can be any meaning which can be expressed by a 'sentence', because according to rule 4 the syntactic category of the expression 'droit' is *s* (sentence).

$$s([and, light, B], S) \rightarrow etclair, s(B, R), \{S \text{ is } R \cdot 0.01\}$$
 (7)

Simplification, applied to rules 7 and 3, can be used to generalise rule 7 replacing it with 8. Rule 6 can be generalised as well replacing it with rule 9.

$$s([and,A,B],S) \to et, s(A,Q), s(B,R), \{S \text{ is } Q \cdot R \cdot 0.01\}$$
 (8)
 $s([or,A,B],S) \to ou, s(A,Q), s(B,R), \{S \text{ is } Q \cdot R \cdot 0.01\}$ (9)

The induction rule of **chunk** replaces a pair of grammar rules such as 8 and 9 with a single rule 10 which is more general, because it makes abstraction of their common structure introducing a syntactic category c2 for binary connectives. Rules 11 and 12 state that the expressions et and ou belong to the syntactic category c2.

$$s([C,A,B],S) \rightarrow c2(C,P), s(A,Q), s(B,R),$$

$$\{S \text{ is } P \cdot Q \cdot R \cdot 0.01\}$$

$$(10)$$

$$c2(\mathsf{and},S) \to \mathsf{et}, \{S \ is \ 0.01\} \tag{11}$$

$$c2(\text{or}, S) \to \text{ou}, \{S \text{ is } 0.01\}$$
 (12)

Simulation Results

We describe the results of some experiments in which three agents try to construct at the same time a conceptualisation and a shared language. Firstly the agents play 700 evaluation games about subsets of objects which can be discriminated using only a single category or the negation of a perceptually grounded category. In this part of the simulation the population reaches a communicative success⁴ of 94% after 100 games and keeps it over that figure until the end of this part of the simulation (see figure 2). Next the agents play 6000 evaluation games about subsets of objects which require the use of perceptually grounded categories as well as unary and binary logical categories for their discrimination. In this part of the simulation the population reaches a communicative success of 100% after playing 3600 evaluation games and keeps it until the end of the second part of the simulation. The data shown in the figure correspond to the average of ten independent simulation runs with different random seeds. These experiments were implemented using the Ciao Prolog system (Bueno et al. 1997).

At the end of the simulation runs all the agents prefer the same expressions for referring to perceptually grounded categories (*up, down, right, left, light* and *dark*). In general, the conceptualisations and grammars constructed by the individual agents at the end of the simulation runs are different, however they are compatible enough to guarantee the unambiguous communication of meanings of the same complexity as propositional logic formulas.

We focus now on a particular simulation run, and analyse the conceptualisations and grammars built by the agents at the end of it (see table 1). All the agents have a recursive grammar rule for expressing formulas constructed using negation, and all of them used the same expression (cp) for referring to the logical category not.

We can observe in table 1 that all the agents constructed logical categories for all the **commutative connectives**

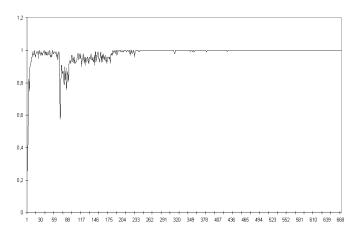


Figure 2: Evolution of the communicative success for a population of three agents.

(and, nand, or, nor, xor and iff), and that they prefer the same expressions (j, wbt, y, nb, dol and ssq, respectively) for referring to such connectives. They use generic grammar rules based on syntactic categories for binary connectives. The syntactic category c1 is associated with grammatical constructions which place the expression associated with the first argument of the connective in the second position of the sentence, and the syntactic category c2 with grammatical constructions which place the same expression in the third position of the sentence. The expressions associated with the logical categories are always placed in the first position of the sentence in these experiments.

We consider now **non-commutative connectives**. All the agents constructed the logical category nif, which corresponds to the negation of an implication, and all of them used the same expression (ml) for referring to this logical category. They used as well the syntactic category c1 for the expression associated with the logical category nif, which means that they all placed the expression associated with the first argument of nif in the second position of the sentence, and the expression associated with the second argument of nif in the third position of the sentence.

None of the agents constructed the logical category *noif*, but this did not prevent them from characterising any subset of objects. Because the formulas [*noif*, A, B] and [*nif*, B, A] are logically equivalent, and all the agents had grammar rules for expressing formulas of the form [*nif*, B, A].

The conceptualisations built by the agents were different as well. Agents a1 and a2 constructed the logical category *if* (logical implication), whereas a3 did not. And agent a3 constructed the logical category *oif*, which agents a1 and a2 did not construct either. Again the lack of these logical categories did not prevent the agents from characterising any subset of objects, because the formulas [*if*, A, B] and [*oif*, B, A] are logically equivalent.

Furthermore the three agents could always understand each other, since agents al and a2 used the same expression for referring to the logical category *if* as a3 for referring to the logical category *oif*, and the grammar rules used by a1

⁴The *communicative success* is the average of successful language games in the last ten language games played by the agents.

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Grammar a1
s([not,X],Q) \rightarrow cp, s(X,P), \{Q \text{ is } P \cdot 1\}
s([X,Y,Z],T) \rightarrow c1(X,P), s(Y,Q), s(Z,R), \{T \text{ is } P \cdot Q \cdot R \cdot 1\}
       c1(nif,R) \rightarrow ml, \{R \text{ is } 1\}
       c1(nor,R) \rightarrow nb, \{R \text{ is } 1\}
       c1(or,R) \rightarrow y, \{R \text{ is } 1\}
s([X,Y,Z],T) \rightarrow c2(X,P), s(Z,Q), s(Y,R), \{T \text{ is } P \cdot Q \cdot R \cdot 1\}
       c2(and,R) \rightarrow j, \{R \text{ is } 1\}
       c2(xor,R) \rightarrow dol, \{R \text{ is } 1\}
       c2(iff,R) \rightarrow ssq, \{R \text{ is } 1\}
       c2(nand,R) \rightarrow wbt, \{R \text{ is } 1\}
       c2(if,R) \rightarrow why, \{R \text{ is } 1\}
Grammar a2
s([not,X],Q) \rightarrow cp, s(X,P), \{Q \text{ is } P \cdot 1\}
s([X,Y,Z],T) \ \rightarrow \ c1(X,P), s(Y,Q), s(Z,R), \{T \ is \ P \cdot Q \cdot R \cdot 1\}
       c1(nif,R) \rightarrow ml, \{R \text{ is } 1\}
       c1(nor,R) \rightarrow nb, \{R \text{ is } 1\}
       c1(or,R) \rightarrow y, \{R \text{ is } 1\}
s([X,Y,Z],T) \rightarrow c2(X,P), s(Z,Q), s(Y,R), \{T \text{ is } P \cdot Q \cdot R \cdot 1\}
       c2(and,R) \rightarrow j, \{R \text{ is } 1\}
       c2(xor,R) \rightarrow dol, \{R \text{ is } 1\}
       c2(iff,R) \rightarrow ssq, \{R \text{ is } 1\}
       c2(nand,R) \rightarrow wbt, \{R \text{ is } 1\}
       c2(if,R) \rightarrow why, \{R \text{ is } 1\}
Grammar a3
s([not,X],Q) \rightarrow cp, s(X,P), \{Q \text{ is } P \cdot 1\}
s([X,Y,Z],T) \rightarrow c1(X,P), s(Y,Q), s(Z,R), \{T \text{ is } P \cdot Q \cdot R \cdot 1\}
       c1(nif,R) \rightarrow ml, \{R \text{ is } 1\}
       c1(nor,R) \rightarrow nb, \{R \text{ is } 1\}
       c1(or,R) \rightarrow y, \{R \text{ is } 1\}
       c1(oif,R) \rightarrow why, \{R \text{ is } 1\}
s([X,Y,Z],T) \rightarrow c2(X,P), s(Z,Q), s(Y,R), \{T \text{ is } P \cdot Q \cdot R \cdot 1\}
       c2(and,R) \rightarrow j, \{R \text{ is } 1\}
       c2(xor,R) \rightarrow dol, \{R \text{ is } 1\}
       c2(iff,R) \rightarrow ssq, \{R \text{ is } 1\}
       c2(nand,R) \rightarrow wbt, \{R \text{ is } 1\}
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Table 1: Grammatical constructions, syntactic categories and lexicons for logical categories built by the agents.

and a2 to express formulas of the form [if, A, B] reversed the order of the expressions associated with the arguments of if in the sentence with respect to the grammar rules used by a3 in order to express formulas of the form [oif, B, A].

Conclusions

We have described some experiments which simulate a grounded approach to the acquisition of the cognitive and linguistic competence required to communicate propositional logic sentences. This encompasses both the construction of a conceptualisation of its environment by each individual agent and of a shared language by the population. The processes of conceptualisation and language acquisition in each individual agent have been based on general purpose cognitive capacities, whereas the construction of a shared language by the population has been achieved using a particular type of linguistic interaction, known as *the evaluation game*, which gives rise to a common set of linguistic conventions through a process of self-organisation.

This work has addressed therefore the problem of the ac-

quisition of both the semantics and the syntax of propositional logic. Trying to learn these two aspects at the same time is more difficult than learning the semantics or the syntax of propositional logic separately. Because the agents must coordinate their linguistic behaviour taking into account only the subset of objects which constitutes the topic of a particular linguistic interaction. This means that a pair of agents can communicate successfully about a particular subset of objects (a topic) even if they use different conceptualisations (formulas) in order to identify the same topic. And this introduces a high degree of ambiguity in the interpretation process the agents have to deal with when they try to construct a shared communication language. In spite of this, the results of the experiments have shown that at the end of the simulation runs the individual agents built different conceptualisations and grammars, but that the conceptualisations and grammars of the agents in the population were compatible in the sense that they guaranteed the unambiguous communication of propositional logic sentences.

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