Studying sign processes in the emergence of communication

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Abstract

Communication depends on the production and interpretation of representations, but the study of representational processes underlying communication finds little discussion in computational experiments. Here we present an experiment on the emergence of both interpretation and production of multiple representations, with multiple referents, where referential processes can be tracked. Results show the dynamics of semiotic processes during the evolution of artificial creatures and the emergence of a variety of semiotic processes, such as sign production, sign interpretation, and sign-object-interpretant relations.

Keywords: Sign; Communication; Semiotics; Artificial Intelligence; Computer Simulation.

Introduction

Computational modeling and simulation of the emergence of semiotic processes, such as language and communication, ,has been consolidating as an important methodology and has a growing community of researchers involves in scientific and technological issues related with such phenomena (Wagner et al., 2003; Nolfi & Mirolli, 2010; Noble et al., 2010). This computational approach have been dedicated to building environments and creatures through which it is possible to simulate the minimum conditions to observe the evolution and emergence of semiotic behaviors. As the main form of interaction between agents, in most of these synthetic experiments, communication has, particularly, been a significant research subject. Primarily, it depends on the production of representations (by an utterer) and the interpretation of them (by an interpreter). Despite the fact that representation processes are in the foundations of communication, little discussion about such processes can be found, such as, the emergence of fundamental types of representations and their referential relations.

We have previously simulated the emergence of interpretation of two different types of representations (symbols and indexes) in communicative interactions (Loula et al., 2010), and have also studied further the cognitive conditions to the emergence of such interpretation processes (Loula et al, 2011). However, the experiments previously done focused only on the emergence of interpretation, with fixed production of a single representation with only one referent. Here we propose to evaluate representation processes in the emergence of both interpretation and production of multiple representations, with multiple referents. To do so, we use a similar scenario of resource collecting, but apply a neural network model as the cognitive architecture for creatures, that can become utterers and interpreters. The experiment involves empirical constraints from studies of animal communication and also theoretical constraints from Peircean pragmatic theory of signs.

In the next section, we review related work on simulation of the emergence of communication. Next, we briefly describe the theoretical principles and biological motivations. We then describe our experiment on the emergence of production and interpretational processes in communication events. Finally, we outline our results and conclusions and point out perspectives on the study of the emergence of sign processes types.

Related work

The emergence of communication in computer simulations is the topic of many works, but discussions on the underlying representational processes find little space in such literature. We review two important ones to reveal this.

Floreano et al (2007) studied the evolutionary conditions that could allow the emergence of a reliable communication system, following biological motivations of animal communication. Groups of robots controlled by neural networks were evolved to adapt to a foraging task. Robots could use a ring of blue light as a signal, as the authors call, to each other. Even though the ring of light was used to cooperate, nothing was discussed on what it represented to the robots or what type of representation could be involved.

In an experiment with artificial creatures in a grid world, Cangelosi (2001) simulated the emergence of communication systems to name edible and poisonous mushrooms. He proposed the emergence of different modalities of representations in this experiment on the evolution of communication. In typifying communication systems, Cangelosi (2001) distinguished between signals, which have direct relation with world entities, and symbols, which in addition are related to other symbols. The simulated creatures were controlled by a neural network which were both evolved and trained in various tasks, and,

at the end, a shared communication system emerged, involving signals and symbols, according to Cangelosi. But he did not described how these signals and symbols were interpreted by the creatures, i.e. if a heard signal was first mapped to a mushroom as its referent, and then to an action, or if it was mapped to an action, with a referent being associated with it.

Other works have also studied the emergence of communication in artificial agents (see Nolfi and Mirolli, 2010, Wagner et al. 2003). Nevertheless, we have not found works that have studied the emergence of different types of interpretations processes and referential processes.

Theoretical and Empirical Constraints

Synthetic experiments are heavily influenced by theoretical principles and biological motivations, and such background should be an essential part of any synthetic experiment (Parisi, 2001). To model the emergence of communication processes based on different types of representation, it is certainly important to look at theoretical models and principles, and also look for biological motivations, and avoid arbitrary or naïve assumptions about the underlying processes.

In computational simulation works dealing with the emergence of communication, there is always something that is communicated from an agent to another one, and that is given various names: signal, symbol, sound, word, expression, or utterance. In most of these works, that which is communicated also seems to have representation capabilities. We have used the term representation in the first section, to emphasize this and also to apply a more familiar word for the artificial intelligence community. Nevertheless, we will now use the expression 'sign', as a technical term in a theoretical background.

A sign is defined, following Peirce (1958), as something that refers to something else, an object (which the sign represents in some aspect) and produces an effect (interpretant) in the interpreter. A sign is also defined by Peirce in relation to communication, as something that mediates between an utterer and an interpreter (Peirce, 1967, MS318), with the sign originating in the first and determining its interpretant in the last (Peirce, 1967, MS11). It is important to notice that a sign is only regarded as a sign if and when it is interpreted, so a sign communicated by an utterer is only a sign to the interpreter, but not to the utterer himself, unless it interprets the produced sign himself.

Sign processes show a remarkable variety. A basic typology (and the most fundamental one), proposed by Peirce (1958), differentiates between iconic, indexical, and symbolic processes. Icons are signs that stand for their objects by a similarity or resemblance, no matter if they show any spatio-temporal physical correlation with an existent object. In this case, a sign refers to an object in virtue of a certain quality which is shared between them. Indexes are signs which refer to their objects due to a direct physical connection between them. Since (in this case) the sign should be determined by the object (e.g. by means of a causal relationship) both must exist as actual events. Spatio-temporal co-variation is the most characteristic property of indexical processes. Symbols are signs that are related to their object through a determinative relation of law, rule or convention. A symbol becomes a sign of some object merely or mainly by the fact that it is used and understood as such by the interpreter, who establishes this connection.

Communication is a process that occurs among natural systems and therefore we followed biological motivations on building our synthetic experiment. Animals communicate in various situations, from courtship and dominance to predator warning and food calls. Following Peirce's definition of sign classes, many animals can actually be capable of communicating by means of diverse types of signs (Ribeiro et al., 2007).

To further explore the mechanisms behind communication, a minimum brain model can be useful to understand what cognitive resources might be available and process underlining certain behaviors. Queiroz and Ribeiro (2002) described a minimum vertebrate brain for vervet monkeys´ predator warning vocalization behavior. It was modeled as being composed by three major representational domains: the sensory, the associative and the motor domains. Different first-order sensory representational domains (RD1s) receive unimodal stimuli, which are then associated in a second-order multi-modal representation domain (RD2) so as to elicit symbolic responses to alarm-calls by a first-order motor representation domain (RD1m).

In order to model the emergence of indexical and symbolic interpretation competences, we must specify the requirements for each and how to recognize them. Indexical interpretation is a direct interpretation of signs, such that the interpreter is guided by the sign to recognize its object as something spatio-temporally connected to it. In the minimum brain model, this corresponds to an individual capable of connecting RD1s to RD1m without the need for RD2. But a symbolic interpretation undergoes the mediation of the RD2 to connect the sign to its object, in such a way that a habit (either inborn or acquired) must be present to establish this association. Thus, in symbolic interpretation,

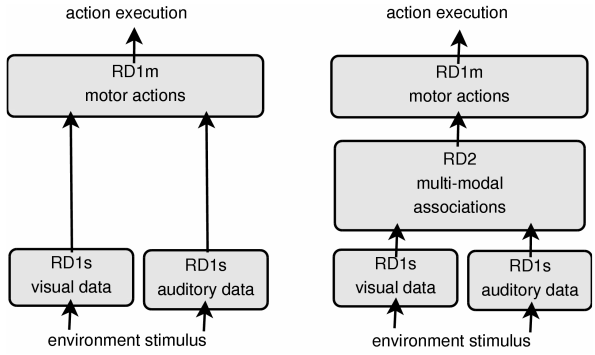

Figure 1: Cognitive architectures for representations interpretations. Left: Type 1 architecture - RD1s are connected directly to RD1m. Right: Type 2 architecture - data from visual RD1s and auditory RD1s can be

RD2 is needed once it is the only domain able to establish connections between different representation domains. To evaluate what conditions might elicit each response type – indexical or symbolic –, we implemented these two possible cognitive processing paths as mutually exclusive paths: either the creature responds to auditory events indexically, with direct motor actions (Type 1 architecture), or the creatures responds to auditory events symbolically, associating them with a visual stimulus and responding as if that was seen (Type 2 architecture) (see figure 1). For an external observer, who only watches the information available to the creature and its motor responses, it may not be possible to see changes in the interpretation process. But the underlying mechanisms behind each sign process are qualitatively different.

The experiment

The scenario to test the conditions for the emergence of semiotic processes is inspired by food foraging behavior of animals. Two types of resources can be found in the environment, with positive and negative values. Resources are differentiated by perceptual features and creatures can produce the two types of signs, which are also perceptually different. Here all creatures are potential utterers and interpreters. An evolutionary process is applied to allow creatures' adaptation to the task of collecting resources, which involves action selection, sensorial categorization, and sign production and interpretation.

The environment is a 50 by 10 grid and the resource (alternating positive and negative in each trial) is placed in one position. Five creatures are placed randomly at each trial, and they are capable of seeing resources within 2 positions distance and hear signs within 25 positions. Each perception of a resource or a sign corresponds to a sequence of bits. A resource is a 4 bit sequence, with positive ones starting with 01 bits and negative ones, with 10 bits. Signs produced by creatures have 3 bits, and can start with bits 01 (called sign 1) or with bits 10 (called sign 2). The other bits are randomly generated.

Creatures can execute a limited set of motor actions: move forward, turn left, turn right, stand still, positive visual taxis, negative visual taxis, positive auditory taxis, negative auditory taxis, protect; and vocal actions: produce sign 1, produce sign 2. Taxis actions are directional motor responses to sensorial input, with positive taxis guiding to the sensorial input position and negative taxis guiding away from it. When a sign is produced by a creature it can be heard by other creatures in the next instant.

Creatures are controlled by a feed-forward neural network with three layers (figure 2), with weights between -2.0 and +2.0 with 0.1 intervals. In type 1 cognitive architecture, auditory middle layer is connected to the output layer, but in type 2 architecture auditory middle layer is connected to the visual middle layer, defining an associative memory between auditory activations and visual activations.

To allow better analysis of neural network activation patterns and to augment the descriptive power of assessing

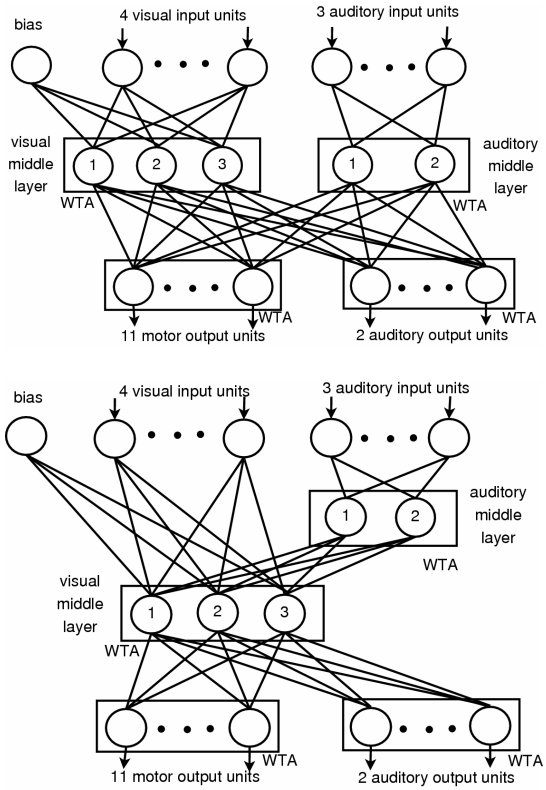

Figure 2: Neural networks used by creatures. Top: Type 1 architecture with direct connection between auditory middle layer and output layers. Bottom: Type 2 architecture with auditory middle layer connected to visual middle layer.

neurons activations, we applied a winner-takes-all (WTA) mechanism to the each middle layer and each output layer. In WTA, only the neuron with the highest positive activation (calculated as the sum of products of inputs and weights) is going to have an output of 1.0. The other neurons within the layer will have a null activation. If no neuron has a positive activation, then all will have null output. Applying WTA activation, both visual middle layer and auditory middle layer perform a localist categorization, with each neuron responding for a given pattern from sensorial input. In the motor output layer and in the vocal output layer, the use of WTA allows only one motor action and one vocal action, at most, to be executed.

The neural networks of all creatures have initially a type 1 architecture with random weights. Evolution allows the creatures to adapt to the task of collecting positive resources and avoiding negative resources. Creatures that stand on the same position as the positive resource gain 10 resource units per instant. When a negative resource is placed on the environment, any creature standing in the same position loses 100 units. Besides, each creature, in any position, not executing a protection action when a negative resource is present, loses 10 units. However, execution of the protection action costs 5 units per instant.

Since this experiment involves the co-evolution of sign production and interpretation, to allow a stable communication system to emerge, selection is done at group level of identical individuals, following conclusions from Floreano et al (2007). The performance of each individual in the proposed task corresponds to the number of resource units collect by their group, composed of cloned individuals (same weights and architecture type).

The population of 500 individuals is divided in 100 groups of 5 clones. Each group is evaluated for 4 to 8 trials, half with positive resource and half with negative one. After groups are evaluated, one individual from the 20 best groups are selected for the next generation. These individuals will be included in the next generation along with 80 new individuals, and each of these 100 individuals will be cloned to form 100 groups of 5 clones again. To generate the 80 new individuals, the 20 best ones go through recombination and mutation. During recombination, if architecture types from parents are not the same, type 1 prevails. Mutation can change each weight to a new value also change architecture type, with 1% chance of going from a type 2 to a type 1 and 0.05% of changing from a type 1 to a type 2.

During the evolutionary process, we observed groups performance in resource collecting task, the auditory middle layer connection (cognitive architecture type), and sign production, along with sign-object relations, sensorial categorization and motor responses.

Results

To evaluate the emergence of sign interpretation and sign production, we simulated the experiment in an initial configuration. There are two cycles. In the first one, 300 generations, creatures did not have the auditory sensor and could not vocalize, and creatures were evaluated for 4 trials, in which they were near the resource. In cycle 2, after 300 generations, creatures were evaluated in 8 trials, 4 without communication, just as before, and 4 with communication, when one creature was placed 1 position away from the resource, but the other 4 were placed far away.

First simulation. During cycle 1, in a few generations, creatures adapted to the task of resource collecting, with the best groups obtaining around 2000 resource units. Creatures quickly acquired a response of protection action for a negative resource seen and a visual taxis response to a positive resource. Visual input categorization was also gradually adjusted, and ended up with creatures categorizing positive resources in neuron number 3 (see neuron numbers in figure 2), negative resources in neuron number 2 and null visual inputs in neuron number 1.

At the start of the second cycle, resource collection performance dropped with the extra trials when most creatures are placed far away from the resource. Observing vocal responses to resources in the start, groups were split between those which vocalized sign 1, sign 2 or no sign. Motor responses to signs, however, were not appropriate yet. The first adaptive use of communication appeared later on, with creatures vocalizing sign 1 to positive resources and responding to it with auditory taxis, with sign 1 categorized in neuron 1 from auditory middle layer. In a further generation, this sign production behavior was expanded; a group vocalized sign 1 to both types of resources. This helped all creatures see the type of resource present in the environment, since they went after the sign utterer, saw the resource, and chose the correct motor response, but with a certain delay because of the distance they had to move. This response was a typical indexical interpretation of the sign that drew interpreters' attention to the utterer, searching for referents spatial-temporally related to the sign.

Later on, one group started a distinguished vocalization for each type of resource, with sign 1 being used for negative resource and sign 2 for positive one. Sign 1 was categorized in neuron 2 in auditory middle layer and had a protection action response. Sign 2 was categorized in neuron 1 with an auditory taxis response. This response dominated all groups after some generations and was the final behavior of all best groups. We could notice that type 1 architecture was dominant during all cycle 2, and therefore indexical interpretation was the only interpretation processes during this simulation.

Second Simulation. A type 2 architecture, with symbolic interpretation, allows the establishment of multi-modal associations and could make auditory signs connect to visual signs. We have previously proposed that symbolic interpretation can act as a cognitive shortcut to an earlier acquired competence, when a cognitive trait is hard to be acquired (Loula et al., 2010). If the interpreter already had appropriate motor responses to visual inputs and this sensor-motor coordination had a high acquisition cost, symbolic interpretation could connect auditory signs to visual signs and reuse the previous acquired competence.

In this second experiment, we modified the scenario of the first simulation by making it harder to learn motor coordination. The WTA activation in the output layer is changed so that the highest active neuron only stays active if its activation (sum of products of neuron inputs and weights) is 1.0 higher than the second highest active neuron. Since weights are between -2.0 and 2.0, this severely limits possible connection weights.

We executed the simulation with this new configuration. Results are shown in figure 5, with the number of collected units and the auditory middle layer connection.

The initial resource collecting performance was much worse than in the first simulation, because most groups remained non-functional with the modified activation of output layer. It took much longer for creatures to respond appropriately to visual inputs. At the end of cycle 1, the number of collected resources by the best groups was similar to the first simulation. At this point, creatures categorized positive resources in neuron number 1 of the visual middle layer, negative resources in neuron number 3, and null visual inputs in neuron 2.

When cycle 2 started and creatures gained auditory sensor and vocal actions, all of them had the auditory middle layer

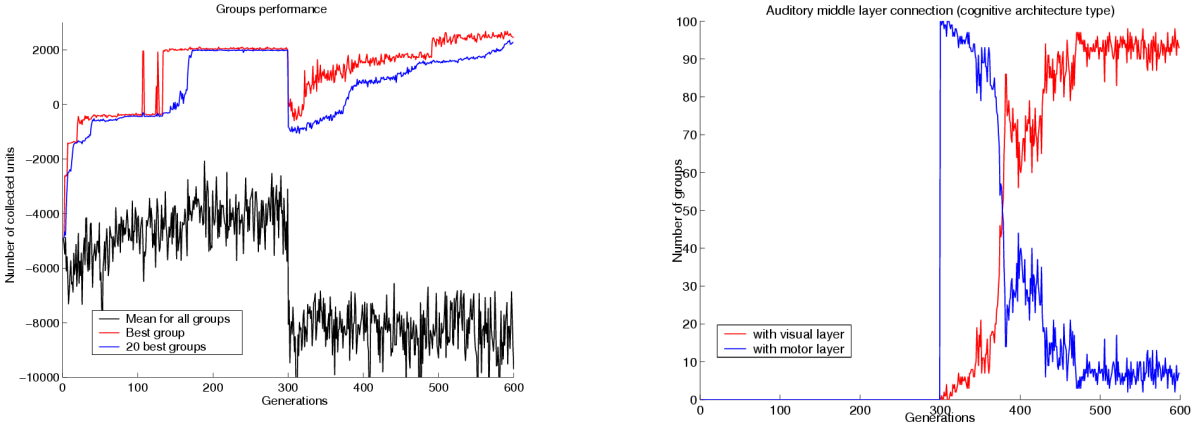

Figure 4: Evaluation of foraging task and auditory middle layer connection along the generations for the second simulation.

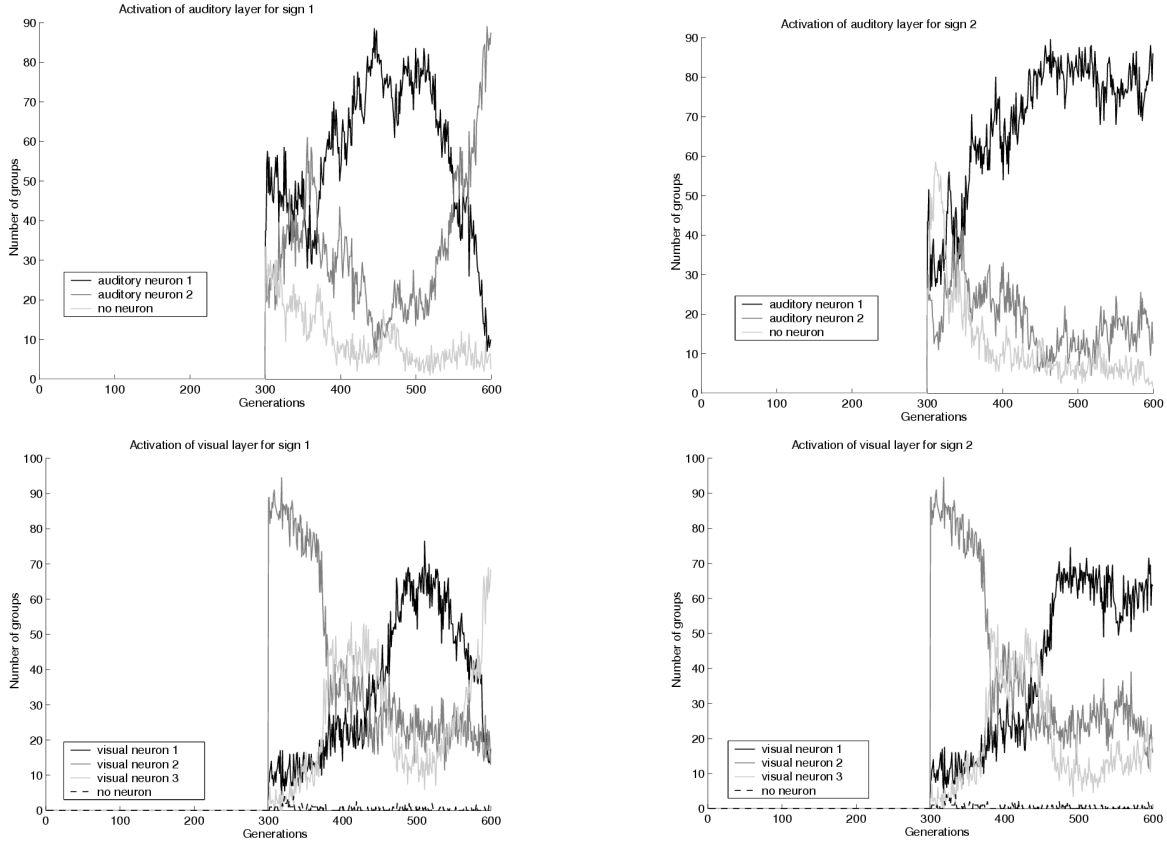

Figure 5: Activation of auditory and visual middle layers for each sign for the second simulation.

connected to the output layer. Different from the last simulation, almost none of the groups vocalized a sign. In the first generations of this second cycle, some groups already had the auditory middle layer changed to connect to the visual layer, but still without vocalizing. After some generations, the first group, to actually produce and interpret signs, vocalized sign 1 when a negative resource was seen, and when this sign was heard, it was categorized by neuron 1 in the auditory middle layer, which in turn activated neuron 3 in the visual middle layer, since creatures in this group had a type 2 architecture. Neuron 3 in visual layer is used to categorize seen negative resources, so an associative memory is established. From then, other groups appear with different strategies, therefore, around generation 400, there was an intense competition between alternative strategies, with different architecture types and different categorizations, as can be seen in figures 4 and 5.

During this dispute, a new strategy appeared with a group of creatures using distinct signs for each resource type: sign 2 for positive resources and sign 1 for negative ones. However, when either signs were heard, they were categorized in the same neuron (number 1) in the auditory middle layer and then connected to neuron number 1 in the visual middle layer, used to categorize seen positive

resources. Even though, diverse signs were produced, sign categorization was indistinct and the same motor response of visual taxis was produced. This was still an adaptive response, since even if a negative resource was present, it guided creatures close to the resource which, when seen, made creatures have a protection action. Note that this is different from what occurred in the first simulation, because in this case there was an interpretation (misleading, however) where any sign always refers to a positive resource, before the creature actually saw the resource.

This undistinguished categorization of signs, however, was not the best adaptive behavior still, since there was a delay in the protection action choice. In a later generation, starting from this strategy, a group categorized signs differently, with sign 2 being categorized in neuron 1 of the auditory middle layer, but sign 1 categorized in neuron 2 which is then associated with neuron 3 in the visual middle layer, used for seen negative resources, ending with an immediate protection action. This becomes the dominant communication strategy, with specific signs being produced by an utterer for each resource type and when an interpreter hears each signs. It internally associates signs with a referent and responds with an adaptive action, without the need of seeing the referent in the environment, so *symbol-based communication* emerged.

Discussion and Conclusion

In previous works, we have simulated the emergence of interpretation processes based on symbolic and indexical signs. Here, besides interpretation processes, we were able to observe the emergence of sign production, sign-object and sign-object-interpretant relations, involving multiple signs, objects and interpretants.

In the first simulation, motor actions could be easily coordinated with sensorial input, and therefore an adaptive behavior evolved into a direct response to the communicated signs. This response defined an indexical interpretation and had two distinct moments for actual interpretation: first, interpreter's attention is directed to the utterer, then, when interpreter gets close to the utterer, it can visualize the object and thus the sign is spatiotemporally associated with the object. At the end of first simulation, this indexical interpretation occurs for sign 2, which is associated with a positive resource, as the interpreter creature performs auditory taxis and finds the utterer creature and the positive resource. In case of sign 1, we cannot say that the creatures interpret it as referring to a negative resource, because upon hearing sign 2, the creatures perform a protection action and stop moving without seeing the negative resource.

Increasing cost of cognitive traits acquisition, we imposed a restriction on neural network's output layer activation in the second simulation. In this case, symbolic interpretation of signs was the adaptive response, confirming our hypothesis that symbolic processes can act as a cognitive shortcut mapping auditory signs to visual categories and reusing visual module mapping to motor actions.

In the second simulation, interpretation of each sign became distinguished with creatures associating each type of sign with a different visual category. Symbolic interpretation of signs emerged as a cognitive shortcut to already established visual-motor connections.

An important step for our experiment was to apply a neural network with a localist activation as the cognitive architecture for artificial creatures. This way, we were able to analyze middle layer categorization of sensorial inputs and what each category activates in the subsequent layer. For type 2 architecture, it was possible to determine the referent of each sign evaluating neural network activation. This model, therefore, allows an objective verification of what signs represent for interpreters in an experiment on the emergence of communication.

Additional investigations on semiotic processes and cognitive processes must be done to complement studies on the emergence of communication and language. We expect that a careful analysis of underlying semiotic processes will bring forth novel findings and stimulate new discussions.

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