Evolution of Communication in Mate Selection

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Abstract

A computational study is conducted to evaluate the hypothesis that mate selection is the evolutionary origin of communication. A population of neural networks is evolved for two cooperative tasks - mate selection and prey capture. Simple codes developed for mate selection serve as an effective stepping stone for prey capture but not vice versa. Mate selection followed by an additional prey capture task is also easier to evolve than both together from the beginning. This result suggests that mate selection may be a first step in the evolution of general communication systems in nature.

Introduction

An important scientific question is to understand the evolutionary origin of language. Communication in nature is believed to have emerged through several stages (Corballis, 2011; Searcy and Nowicki, 2010; Bradbury and Vehrencamp, 2011). Initially, non-signals (neutral traits/natural cues) like breathing patterns and urination were ritualized as courtship signals and territorial markings, respectively (Smith, 1997; Hinde, 1997). Next, complex social and environmental pressures required individuals within a group to cooperate and compete in diverse environments (Nowak and Krakauer, 1999; Corballis, 2011). Such interactions gradually lead to more complex signals, and eventually to a proto-language (Bickerton, 1990). Subsequently, signals developed for a specific evolutionary purpose were exapted and used for other functions (Logan, 2008; Gould, 2002). These steps are believed to have been crucial in the evolution of human language.

Without direct evidence, it is difficult to verify that these steps indeed took place, and to identify the actual behaviors involved. However, simulating language evolution using modern computer science tools can be insightful. Through simulated experiments, this paper evaluates the hypothesis that mate selection is the evolutionary origin of communication. Because mate selection is essential in sexual organisms, is closely related to fitness, and is a social interaction, it is a compelling candidate. During mating, communicative signals emerge naturally to help identify suitable mates. As

soon as such signaling is possible, it may be exapted to serve other social behaviors as well.

In this paper, a series of computational evolution experiments are performed to simulate the origins of mating signals and their exaptation for other social tasks. Communication is evolved in a population of artificial agents in two cooperative tasks: mate selection task and prey capture. In nature, communication during the mating process is used to discern suitable partners and successfully realize reproduction to produce fit offspring (Hauser, 1997). Analogously, during simulated mating, a pair of randomly selected agents from the population exchange signals and determine their compatibility. Initially, this process is based on direct display of traits. In the second phase, simple codes emerge that encode these traits. These codes can be seen as vocal/visual gestures used by individuals in nature.

In the third phase, the successful population from the mate selection experiment is evaluated in an additional task - prey capture. This task requires a more sophisticated communication mechanism on the part of agents in order to time their attack to capture the prey. They can leverage the communication abilities developed for mate selection and quickly achieve the prey capture goal. This adaptation turns out to be computationally faster than evolving communication for prey capture first, or evolving for both mate selection and prey capture at the same time. The experiments thus demonstrate that complex signaling in tasks like prey capture could have been exapted from a simpler task such as mate selection. The computational results thus support the theory that mate selection is the origin of communication.

Prior Work

Although several prior computational studies demonstrated the evolution of communication in intelligent agents, most did not focus on possible biological origins of this process. The environments and tasks were carefully crafted so that communication was necessary for the agents to be successful, and the focus was simply on developing a common communication code (Nolfi and Mirolli, 2010; Steels, 2003, 2005; Tuci, 2009; Werner and Dyer, 1990; Rawal et al.,

Output Message **Mate/Don't Mate Decision** **Move/Don't Move Decision**

2-bit feature e.g 01

Input Message **Prey Distance** **Mate Selection/Prey Capture Switch**
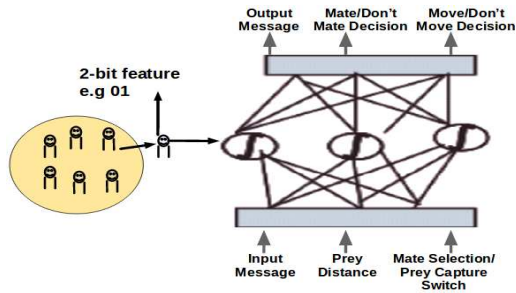
Figure 1: **Population of Agents** - Each agent in the population consists of a 2-bit feature and a feedforward neural network. The feature is required during mate selection to determine agent compatibility, and the network implements the behavior of the agent.

Features	0 0	0 1	1 0	1 1
0 0	1	0	0	1
0 1	0	1	1	0
1 0	0	1	1	0
1 1	1	0	0	1

Figure 2: **Feature-Compatibility Matrix** - Compatibility of any two agents is determined by the compatibility of their 2-bit features. An entry of one in this matrix indicates that the two features are compatible and a zero indicates that they are not.

2012).

(Mirolli and Parisi, 2010) studied the role of kin-selection in the emergence of the first signalers and receivers. (Quinn, 2001) demonstrated how simple behavioral cues can be selected by evolution and subsequently used as signals. (Greeff and Nolfi, 2010) evolved implicit and explicit signaling between a team of foraging robots, demonstrating that . Importantly, the individuals in these experiments are homogenous i.e a single genotype is cloned to generate a team. This design makes the task of evolving a common code easier. In contrast in nature, although communicating individuals do share a common code (i.e they have a common agreement on the meaning of the signals) their individual characteristics like size, strength and speed vary. Therefore, a heterogenous population of neural networks is evolved in this paper. An important result is that even with such heterogeneity, a common encoding scheme emerges.

(Mitri et al., 2010) highlighted the importance of group selection in the evolution of honest signaling. Similarly, the experiments designed in this paper are cooperative i.e the team fitness reward is equally distributed between the participants.

The paper is organized as follows. The experimental setup is described first, including the network architecture and the two tasks, mate selection and prey capture. This section also explains the two cooperative tasks - mate selection and prey capture. The results of the five experiments - explicit and implicit communication in mate selection and the three ways of evolving communication for the two tasks - are then presented. The computational and biological insights and future extensions to competitive mating are discussed in the end.

Experimental Setup

A common network architecture is evolved to perform both the tasks of mate selection and prey capture, as described below. Each individual agent consists of a neural network and a 2-bit binary feature (See Figure 1). The 2-bit feature is used during the mate selection task to determine whether the agents are compatible or not. The neural network controls the behavior of the agent during simulation.

Neural Network Architecture

An agent's neural network consists of a single hidden layer with 10 hidden neurons and four output neurons. The first two output neurons are used as the output message of the agent. The third output is used during mate selection task to indicate mating decision i.e mate/dont-mate. The fourth output is used during prey capture task to indicate agent movement decision i.e move/don't-move. All nodes have a sigmoidal non-linearity and therefore the output value of each node is a real number ranging between 0 and 1. The output node values are rounded off to 0/1 before being used.

In each experiment, there are at least four input neurons - two messaging inputs for receiving messages from other agents, one prey-distance input for sensing prey (integer values between [0-2] and set to -1 during mate selection) and one task-switch input to indicate the type of current task (1 during mate selection and 0 otherwise). In Experiment 1, there are two additional network inputs that provide the agent its own feature value. The network architecture is fixed over the course of evolution. At the start of simulation, a population of 64 agents is generated with random neural network weights and a random 2-bit feature. During each evolutionary generation, 3000 trials of a given experiment are performed on a pair of randomly selected networks. Binary tournament selection is used to select parent population. To generate the offspring population, the neural network weights of the parent population are mutated with a probability of 0.4 by adding a Cauchy-distributed random value to it. Note, that the 2-bit feature value associated with each agent is not mutated and is directly transferred from parent to offspring.

Two cooperative tasks are used to evaluate the population - mate selection and prey capture as described below.

2-bit Output message   **Decision Output**

Inputs tied to -1   **Message from the other agent**

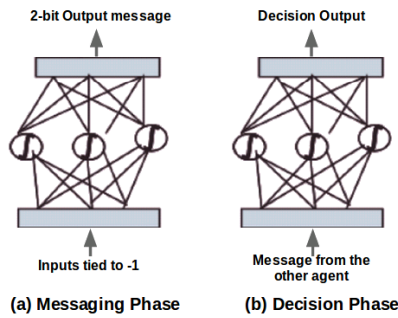**(a) Messaging Phase**   **(b) Decision Phase**

Figure 3: **Agent Behavior** - The agents implement their mate-selection and prey-capture behavior through two network activations: (a) Messaging Phase - The network input nodes dedicated to receive messages are tied to a constant value of -1. In mate selection, they output a code for their 2-bit feature. In prey capture, they output a 2-bit code for distance to the prey. The 2-bit message is then given to the other network as input. (b) Decision Phase - The networks are activated and their output decision node value is rounded off to give a 0/1 decision (mate/don't mate or move/don't move. In this manner, the networks communicate their states first and then decide upon a proper action to take.

Mate Selection Task

During the mate selection process in nature, males often try to communicate their characteristics through simple cues, gestures and more sophisticated signaling (Stoffer and Walker, 2012; Johansson and Jones, 2007). These signals convey the fitness of the individual (and therefore fitness of a future offspring) and thus influence the prospects of mating with the female.

The mate selection task emulates this process. A 2-bit feature associated with an agent represents its individual characteristic in this artificial setting. For simplicity, the population is not divided into males and females. Instead, two agent networks are randomly selected from the population and they exchange messages to make a mate/dont-mate decision. The ground truth for this mating decision is predefined in a randomly generated feature-compatibility matrix. One example of such a matrix is shown in Figure 2. A 1 in the matrix indicates that the two agents are compatible while a 0 indicates that they are not. From a biological perspective, compatibility between two agents can be viewed as the fitness of their offspring i.e if two highly compatible agents decide to mate, their offspring will have a higher fitness than the offspring of two incompatible agents.

Such a mating task is cooperative in that none of the agents receive fitness increment unless both of them make the correct mating decision. Both agents receive a fitness increment of one for each correct mating decision. For example, feature values 01 and 10 in Figure 2 are compatible and therefore two agents with these features receive a fitness

increment of one if both decide to mate and zero if otherwise.

During this task, the task-switch and prey-distance inputs are set to constant values of 1 and -1, respectively. Each trial consists of two phases (Figure 3). In the first phase (defined as the messaging phase), the two neural networks are activated (with messaging input tied to constant value of -1) and the first two output nodes are sampled for their values. The two output real values are then rounded off to obtain a 2-bit output message. In the second phase (the decision phase), this 2-bit output message from one network is given as messaging input to the other network. After a second network activation, the value at the output mating decision node is rounded off to generate a mate/dont-mate decision.

Note that in the current simulations the two paired networks do not undergo actual mating (i.e crossover) based on their mating decision. Instead, offspring is generated through mutations of most fit parents. This simplification helps focus the study on the question of how mate selection may act as an origin for communication. However, to this end it is essential that the agents are not artificially constrained to generate any specific message type during the messaging phase. The only feedback the agents receive (indirectly, through fitness) is based on the correctness of their mating decision.

An additional constraint is added to ensure that each feature is equally represented in the population over the course of evolution. The initial population of size 64 is divided into four sub-groups of size sixteen each - one group for one feature type. After all networks have been evaluated in each generation, a binary tournament is performed on each feature group separately to obtain sixteen offspring. Since the parent feature is directly transferred to offspring and is unaffected by mutation, the feature representation in population remains fixed at sixteen. This restriction prevents any feature in the population from becoming dominant (which would remove the need to communicate).

Prey Capture Task

Prey capture in nature often involves cooperation and communication on the part of agents. This task simulates such a scenario with a fixed prey in a discrete, deterministic world. At the start of each trial, two agents (randomly selected from the population) are positioned at random distances apart from the prey (Figure 4). The agent agents can sense the distance to the prey but cannot sense the distance to the other agent. They have two possible actions - either move towards the prey or stay in their current position. With each agent move towards the prey, the agent-prey distance decreases by one. The prey is considered captured when the two agents pounce on the prey in the same time step. In order to be successful, the agents need to communicate when they are ready for the capture.

The task-switch input neuron is set to a constant value

of 0 to indicate prey capture task, and the prey distance inputs to the proper value to indicate distance. Similarly to the mate selection task, each time step in a trial is divided into two phases - messaging phase and decision phase. The output movement decision node of the network determines the agent action : move/dont-move. agent agents receive a fitness increment of one on capturing the prey and zero otherwise. Again, agents are not constrained to generate a specific message type but must evolve one that works.

Measuring Success

In each experiment, data is collected over 150 runs and averaged. Since fitness distribution is cooperative for each task (i.e in a given trial, a pair of individuals receive fitness of one only if both make correct predictions), it is very difficult to achieve 100% population success. Therefore, a population is deemed successful if at least 25% of its individuals have an average fitness of greater than 75% of the maximum fitness. This success criteria ensures that a significant fraction of population develops common communication code to solve the task. The total number of generations required to evolve a successful population is used as a quantitative measure to compare different experiments.

The next section describes the experiments in detail.

Experiments

The first two experiments demonstrate that a common code does evolve in mate selection. Experiments 3-5 then evaluate the hypothesis that mate selection is an effective first step in evolving a more general communication system.

Experiment 1 - Mate Selection with Feature Inputs

In the first experiment, the population is evaluated in the mate selection task. Each agent (in the randomly selected pair) is explicitly provided its own 2-bit feature as input during the messaging phase. The 2-bit message generated at its network output is then given as input to the other agent in the decision phase. In this setting, the neural network thus has four active input nodes - 2-bits for agent feature and 2-bits for sensing the output message of the other agent.

On average after 11 generations, the best agent pair evolve a simple signaling system where they send their exact input feature as a message during the messaging phase. These messages are similar to the explicitly visible characteristic of an individual in nature - for example its size and strength. The messages thus do not represent a communication code; they are simply a direct expression of the underlying characteristic. They serve as a baseline for evolving a communication code.

Experiment 2 - Mate Selection with Hidden Features

In the second experiment the setup is modified to allow an actual communication code to emerge. During the messag-
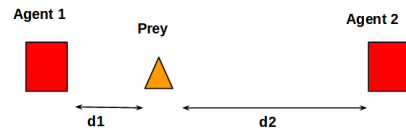

Figure 4: **Prey-capture task** - There is one static prey and two agents positioned random distances (0 $\leq$ d1$\leq$ 2, 0 $\leq$ d2$\leq$ 2)apart from the prey. At each time step, the agents can either stay still or move one distance unit towards the prey. To be successful, they are required to capture the prey by stepping on its location at the same time step. The agents can sense the prey distance but not the distance to the other agent. Thus, they need to develop a communication system to coordinate their movements.

ing phase, the 2-bit input feature is hidden from the agent i.e not given to the neural network as input. Evolution has to figure out this feature and develop a code for communicating it. Thus, only messaging inputs of the network are active during the decision phase.

On average, after 31 generations, the agent pairs develop to send an encoding of their input features during messaging phase. These encoded messages provide the necessary information to distinguish compatible agents from the not-compatible ones. In certain cases, the encodings are shared between compatible individuals. The encoding evolved for the feature-compatibility matrix shown in Figure 2 is one such case. Since feature values '00' and '11' are compatible with both themselves and each other, evolution discovers a shared message (e.g '00') to recognize these two features (exact code values vary across different runs). In this manner, a true communication system evolved to express the features hidden from the agents. This system can be exapted to other tasks, as shown below.

Experiment 3 - Mate Selection followed by Mate selection and Prey Capture

This experiment simulates how simple communication that was initially evolved for mate selection can be exapted for the more complex prey capture. The population is first evolved for the mate selection task without feature inputs (Experiment 2). The successful population is then evolved in two tasks - both mate-selection and prey-capture together.

During the mate selection task, prey-distance input is tied to a constant of -1 and task-switch input is set to 1. The feature-compatibility matrix shown in Figure 2 is used. Once a quarter of population achieves an average fitness of more than 75% of the maximum fitness in the mate-selection (criteria of success as described earlier), an additional prey capture task is introduced. In each generation, the population is separately evaluated in the two tasks. Fitness of an individual in the population is its average fitness in the two tasks. The input/output communication channels developed

during the mate selection task are reused during prey capture task. The experiment terminates once the population achieves the average fitness goal for both the tasks (i.e quarter of population with an average fitness greater than 75%). During the course of evolution, feature representation in the population is kept constant (as described in the mate selection task).

During the prey capture task, the prey distance input to the network is set according to distance and task-switch input is set to 0. Agents are positioned at random distances from the prey. The maximum initial agent-prey distance is two steps and the minimum distance is one step. Agents can choose to move/dont-move towards the fixed prey by activating their movement output node.

The evolved communication codes become quite sophisticated. When the first agent is at a distance of more than one from prey, it sends a code (e.g '00') signaling that it is moving and has yet to reach next to the prey. At a distance of exactly one step from the prey, it changes its output (e.g '11') indicating that it is now ready to capture the prey. The second agent ignores these signals from the first agent while it is not ready for prey capture (i.e it is at a distance of more than one step from prey), and instead it moves towards the prey. Once the second agent reaches a distance of exactly one step from prey, it starts paying attention to the signal from the first agent. If the first agent is ready for prey capture (i.e it signals '11'), both agents move to the prey location to capture it. Otherwise, the second agent selects the dont-move option and waits until the first agent is ready (outputs '11').

Solution to the first task (mate selection) evolves on average in 31 generations (same as in experiment 2). It takes on average 55 additional generations to evolve a population that solves both tasks. Thus on average a total of 86 generations are required to solve the two tasks together completely. The entire profile of this process is shown in Figure 5

Interestingly, the codes used during mate selection task are reused during the prey capture task. For example, one pair of agents used the code '11' to communicate their own feature in the mate selection task. After evolving in the prey capture task, their descendants used this same code to indicate readiness for prey capture. In addition, they evolved a second signal ('01') to indicate that they were moving towards the prey. In this manner, the mate selection gave them a starting point that was modified for the new task.

Experiment 4 - Mate Selection and Prey Capture Coevolution

In this experiment, communication is evolved for mate selection and prey capture simultaneously. Starting from the first generation, each agent is evaluated in both tasks, and their fitness is averaged across tasks. Thus, a population is deemed successful if it achieves the average fitness goal for both tasks. Feature representation in the population is kept constant by performing binary tournament selection on each feature sub-group separately, as before.

A successful population evolves on average in 123 generations. As shown in Figure 5, coevolution of both tasks tends to take longer than when mate selection is evolved first. A successful population is evolved on average in 123 generations (vs. 86 generation in Experiment 3; $p < 0.066$). Thus mate selection serves as a useful stepping stone for other tasks.

Experiment 5 - Prey Capture followed by Mate Selection and Prey Capture

This experiment is similar to Experiment 3, except the roles of mate selection and prey capture are reversed. The population is first evolved to solve the prey capture task and then to solve both mate selection and prey capture. The input/output communication channels developed during the prey capture task are exapted to the mate selection task.

Initially, during the prey capture task, the agent features are irrelevant (since agent compatibility information is not used). Therefore, binary tournament is performed on the whole population irrespective of the feature type. Once a successful population evolves for the prey capture task (again, a quarter of the population performing at 75%), mate selection is introduced as a second task for evaluation. Since mate selection requires information about agent compatibility, 2-bit features are assigned randomly to individuals in the population at that point. Subsequently, binary tournament is performed on each feature group separately as usual in mate selection.

A successful population evolves on average in 183 generations. As shown in Figure 5, exaptation from prey capture to mate selection takes longer than both exaptation from mate selection to prey capture (Experiment 3) and their coevolution (Experiment 4); these differences are statistically significant $p < 0.0001$. This result suggests that it is not simply the incremental nature of exaptation that matters but the actual steps; mate selection is a better stepping stone for building a general communication system than prey capture is.

Discussion

As shown in Figure 5, it is easiest to evolve a population for the two ecological tasks of mate selection and prey capture, if it is first evolved to solve the mate selection task. A prerequisite for communication includes the ability to output meaningful signals and interpret the received input signals (Mirolli and Parisi, 2010). The mate selection task builds an initial structure to support this mechanism. The signals that evolve for mate selection are simple and fundamental: they map a single state to a single symbol. Once created, this communication mechanism can be be co-opted for more difficult tasks like prey capture, where multiple states must be mapped to the same symbol, or multiple symbols have the
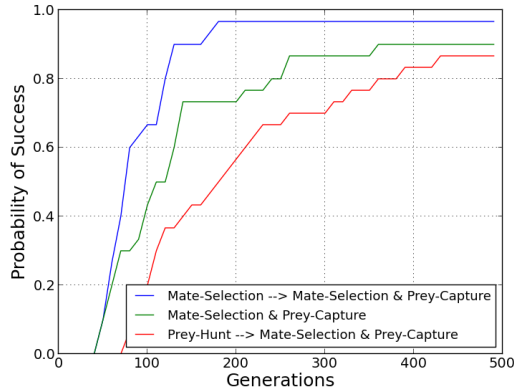
Figure 5: **Probability of success throughout evolution** - This graph shows how likely evolution is to discover a successful population (where a quarter of the population is successful 75% of the time in the two tasks of mate selection and prey capture) by a given generation. The most effective method is to evolve mate selection first, followed by additional prey capture. Evolving both at once from the beginning is weaker, but still stronger than evolving for prey hunting first followed by mate selection. Thus, communication evolved for mate selection makes it easier to evolve communication for another task. This result suggests that mate selection is a likely first step in the evolution of communication.
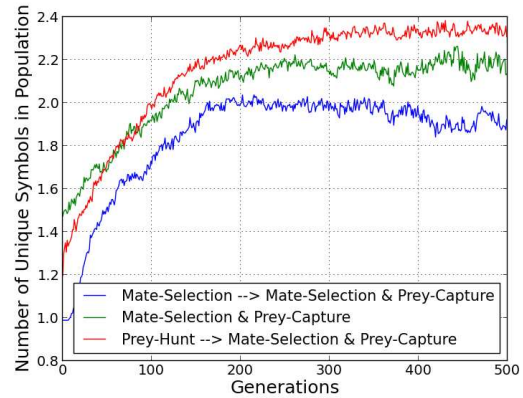

Figure 6: **The Number of Communication Symbols Evolved** - With prey capture, there are many states when the agent is not ready, and therefore some redundant symbols are likely to evolve to signal these states (e.g 2.4 symbols on average). In contrast, mate selection often results in a one-to-one mapping from states to symbols. Therefore, the final communication system built on mate selection is likely to be simpler (about 2.0 symbols on average) and therefore easier to discover than with the alternatives. The population success criterion was increased from 75% to 90% of maximum fitness in this comparison to reduce variance.

same meaning. Indeed, networks evolved initially for mate selection end up using significantly fewer symbols than co-evolved or initial prey-capture networks (with $p < 0.001$; Figure 6). From a computational perspective, the mate selection task thus provides a better stepping stone to construct general communication than prey capture.

Future Work

The mate selection process in these experiments was cooperative in that both partners aimed at determining compatibility, and there was no conflict of interest. While such mate selection is seen in nature, competitive mate selection is more common (Andersson, 1994). That is, one of the genders, usually female, chooses the mate, and the other gender, usually male, tries to convince that he is a good choice. Competitive mate selection likely originates from the asymmetry in gender roles: Females try to maximize quality and males quantity of their mates. Competitive mating thus leads to behaviors where males may try to communicate dishonestly, exaggerating their quality, and females try to estimate what the males' actual quality is. On the other hand, most other communication between animals is by necessity cooperative. For instance in hunting, the individuals need to communicate honestly in order to be effective. An interesting

scientic question therefore is: How can an eventually mostly cooperative communication system be built on a competitive origin? This question will be studied in future extensions of the simulations described in this paper.

Conclusion

This paper evaluated computationally the hypothesis that mate selection is the origin of communication in nature. That is, communicative signals emerge naturally to help identify suitable mates; as soon as such signaling is possible, it is exapted to serve other social behaviors, such as prey capture. Computational simulations verified this hypothesis in a simplified setting where direct displays of traits evolved to coded communication of traits, and were then exapted to use in coordinating a prey capture. This sequence turned out to be faster than evolving prey capture first or both together from the beginning, suggesting that mate selection may indeed be an effective stepping stone to construct general communication systems.

Acknowledgements

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