Effects of Visual Sensory Range on the Emergence of Cognition in Early Terrestrial Vertebrates: An Agent-Based Modeling Approach

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Abstract

As water dwelling vertebrates began to progressively evolve features that enabled them to survive on land, they also developed larger eyes, which would have considerably increased their range of vision above water. This increase in visual range may have facilitated their exploitation of new food sources on land and promoted increased cognitive capacity in the form of planning (MacIver et al., 2017). In this study, we use a multi-level agent-based model to attempt to replicate the dynamics of the hypothetical evolutionary scenario described above. To do so, we use a novel method called agent-centric Monte Carlo cognition (ACMCC) (Head and Wilensky, 2018), which allows us to represent the agents' cognition in a quantifiable manner by performing micro-simulations in a separate agent-based model. In our simulations, we observe that as a population that is adapted to live on land emerges, their mean eye size and cognitive capacity increase.

Introduction

When vertebrates first began to move onto land, they experienced morphological changes, progressively trading their fins for limbs, and their gills for lungs. This better adapted them to their new terrestrial environment (Long and Gordon, 2004). As they emerged from the water, it is likely that they gained much more visual information about their environments. This information gain may have driven the emergence of more advanced cognition and complex planning abilities (Kohashi and Oda, 2008; MacIver, 2009; MacIver et al., 2017; Mugan and MacIver, 2018).

In this study, inspired by MacIver et al. (2017), we hypothesized that terrestrial tetrapods would develop higher planning capacities than their aquatic counterparts due to an increase in their visual perception space.

Methods

We use a multi-level agent-based modeling (ABM) approach in this study. ABMs have been a powerful tool for simulating complex systems (Wilensky and Rand, 2015). We use a novel method called agent-centric Monte Carlo cognition (ACMCC) (Head and Wilensky, 2018) in order to model animal cognition. Each agent has a mental representation of its environment which is modeled using a separate cognitive ABM. Agents use this cognitive ABM to run "micro-simulations" in order to predict the outcome of different actions they may choose. The product of the number of actions they simulate and the length of these simulations give us an estimation of their cognitive capabilities. We used NetLogo (Wilensky, 1999) along with the recent LevelSpace extension (Hjorth et al., 2015) to implement our model.

Overview

In our model, half the world is underwater (low visibility), and the other half is on land (high visibility). The tetrapods in our model are initially adapted to water. In time, these aquatic tetrapods evolve and some of them transition to life on land. "Food" in our model represents invertebrates available as prey on both water and land. The tetrapods in our model have the following evolvable parameters:

Eye size: the radius of the agents' fields of vision.[1] For the sake of simplicity, we assume that agents have a field of vision of 360 degrees. The effect of eye size on visual range on land is much great than that of underwater in accordance with previous studies (MacIver et al., 2017).

Mobility: how well adapted the tetrapod is to life underwater or on land. This characteristic aims to capture the morphology of the tetrapod as it undergoes the fin-to-limb transformation and how this relates to its locomotion (Long and Gordon, 2004).

Energy: the level of nutrition (energy) of the tetrapod. Tetrapods gain energy from consuming food and lose energy as they move, plan actions, or reproduce.

Simulation Number: how many micro simulations the agent performs at each time step. It models the ability to consider a number of different scenarios before deciding on the best course of action.

Simulation Length: the number of steps in each micro simulation that the agent performs at each time step. It models the ability to think multiple steps ahead before deciding on the best action.

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[1] We note that this is a proxy for how far a tetrapod can see and includes factors such as eye size, eye complexity and development.

Planning

To modeling animals' planning and decision-making skills we allowed the modeled tetrapods to run "micro simulations" in which they could simulate the consequences of a variety of actions and select the action (direction of movement) that resulted in the greatest expected energy gain. A micro simulation is a simplified version of the macro model.[2] Each tetrapod loses an amount of energy proportional to the product of its simulation number and simulation length parameters, representing the cost of cognition. Furthermore, the size of the world in a micro simulation is limited to the initiating agent's visual range. We can think of this as a Partially Observable Markov Decision Process, which has previously been used to model animal decisions (Head and Wilensky, 2018; Mugan and MacIver, 2018; Miller et al., 2017).

Actions

At each time step, each tetrapod moves, consuming energy. The food remains stationary. The speed of an agent's movement depends upon its mobility value and whether it is on land or underwater. The amount of energy consumed depends on an agent's mobility value, its eye size, and whether it is underwater or on land. If a tetrapod reaches food, it kills the food and gains energy. If the energy value of a tetrapod goes below zero, it dies. A tetrapod may reproduce, dividing its energy between it and its offspring. The offspring inherits its parent's parameters but undergoes mutation at a predetermined rate. At each time step, there is an adjustable probability that a new piece of food will appear.

Discussion

The initially abundant food sources on land become scarce following tetrapods transition to land. Then, as can be seen in Figure 1, the terrestrial tetrapods develop larger eyes and an increased cognitive capacity (simulation length x simulation number), likely due to the selective pressure to remain competitive in consuming the now-scarce food. [3] Even though we chose to model a scenario in which only the predators are able to plan, we expect our results to generalize to a broader context in which prey also gain an advantage from planning by being able to better avoid predators.

Conclusion

The results of our model support the idea that increased visual perception allowed the early tetrapods to look further into time as well as space, thus aiding the selection of abilities such as planning, strategic thinking, and complex decision-making. This might be an important factor in explaining the emergence of intelligent life.

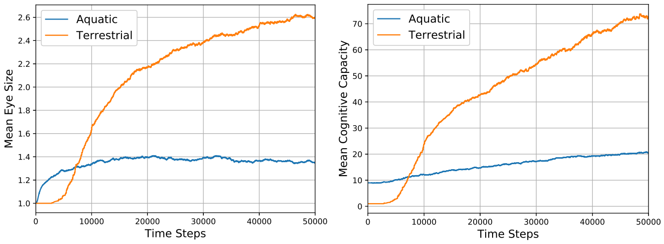

Figure 1: Mean eye size (left) and mean cognition capacity (right) of the terrestrial (mobility > 0) and aquatic (mobility ≤ 0) populations as a function of time.

References

Head, B. and Wilensky, U. (2018). *Agent Cognition Through Micro-simulations: Adaptive and Tunable Intelligence with NetLogo LevelSpace: Proceedings of the Ninth International Conference on Complex Systems*, pages 71–81.

Hjorth, A., Head, B., and Wilensky, U. (2015). LevelSpace NetLogo extension. http://ccl.northwestern.edu/levelspace/index.html, Northwestern University, Evanston, IL.

Kohashi, T. and Oda, Y. (2008). Initiation of mauthner- or non-mauthner-mediated fast escape evoked by different modes of sensory input. *Journal of Neuroscience*, 28(42):10641–10653.

Long, J. A. and Gordon, M. S. (2004). The greatest step in vertebrate history: A paleobiological review of the fish-tetrapod transition. *Physiological and Biochemical Zoology*, 77(5):700–719. PMID: 15547790.

MacIver, M. A. (2009). *Neuroethology: From Morphological Computation to Planning*, pages 480–504. Cambridge University Press.

MacIver, M. A., Schmitz, L., Mugan, U., Murphey, T. D., and Mobley, C. D. (2017). Massive increase in visual range preceded the origin of terrestrial vertebrates. *Proceedings of the National Academy of Sciences*, 114(12):E2375–E2384.

Miller, K. J., Botvinick, M. M., and Brody, C. D. (2017). Dorsal hippocampus contributes to model-based planning. In *Nature Neuroscience*.

Mugan, U. and MacIver, M. A. (2018). How sensory ecology affects the utility of planning. In *2018 Conference on Cognitive Computational Neuroscience*.

Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/, Northwestern University, Evanston, IL.

Wilensky, U. and Rand, W. (2015). *An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo*. The MIT Press.

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[2] We note that we chose a model of cognition in which we could explicitly define and measure intelligence. Our specific model of cognition relies on an explicit central representation of the environment that can be manipulated, however we expect that our results could still be observed with different models of cognition.

[3] Changes in the environment and further specialization and adaptation of species could explain the variation in eye sizes of contemporary intelligent species without undermining our assumptions.