

Learning What to Eat: Studying Inter-relations Between Learning, Grouping, and Environmental Conditions in an Artificial World

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Abstract. In this paper we develop an artificial world model to investigate how environmental conditions affect opportunities for learning. We model grouping entities that learn what to eat in a 2D environment. We study diet development and focus on the social consequences of individual learning in relation to different environmental conditions.

We find that homogeneous and patchy environments have opposite effects on learning. Homogeneous environments lead to diet differentiation, while patchy environments lead to diet homogenization among the members of a group. In patchy environments, grouping results in a social influence on individual learning and could be the simplest way to achieve social inheritance of information. Moreover, diet differentiation can affect group cohesion, leading to group fragmentation along dietary lines. This suggests that if social learning leads to diet homogenization, it could play a role in maintaining group cohesion.

1 Introduction

Social learning and foraging cultures appear to have considerable impact on the foraging behavior of non-human primates. Different food extraction techniques are employed by different groups of chimpanzees [1] and orang-utans [2], and to lesser extent in, for example, capuchin monkeys [3]. These, together with differences in diet that cannot be attributed to ecological factors, constitute evidence for foraging cultures. Social learning constitutes a non-genetic means of information transfer and seems to be an important addition to genetic evolution of behavior.

The discussion on social learning centers mainly around the underlying cognitive mechanisms [4] and its adaptive value [5,6]. Social learning is thought to be adaptive because it reduces the costs of trial and error learning. It is clear, however, that there are many more factors that determine whether social learning and culture can occur. For example, given sufficient cognitive abilities, the emergence of culture depends on the need for sophisticated food extraction or

processing [7], group size [8,9] and tolerance within a group [2,10]. From this perspective, Coussi-Korbel and Frigaszy [11] have developed a speculative framework where they relate social learning opportunities to primate social dynamics (from egalitarian to despotic). Their main tenet is that despotism increases directionality and reduces the scope for social learning.

In our study we focus on the environmental opportunities for individual and social learning. We aim to gain an understanding of the types of interactions and feedbacks that arise when groups of individuals forage and learn in a given environmental background. We have developed an artificial world where foraging individuals have to learn what to eat. We model individuals which form groups and interact with their environment in a way that is sufficiently representative for primates, yet remains simple enough to understand. An important aspect of our model is the flexibility of interaction between model components, allowing for self-organizing processes to arise. In the present study we look only at individual learning, but we relate our results to social learning and social information inheritance.

2 Model

Our artificial world is a 2D environment with a high number of resource types in which individuals forage in groups. The model is constructed using a combination of a multi-layer cellular automata for the environment and an individual-oriented component for entities that learn to forage. Unlike most ecological models, predator-prey relations are not predefined. Individuals must learn what to eat, so defining their own ecological dynamics.

Local ecological and social context, and individual internal state, determine individual behavior. In this way foraging is dependent on the ecological and social opportunities that arise. Therefore learning is not a default strategy, but depends on who and what individuals can see. Furthermore, learning is linked to genetically determined gastro-intestinal digestive capacity, thus determining the types of resources that can be digested. The model, as used in this study, is described below.

2.1 Environment

The environment is a 20 layer cellular automata (CA) where each layer represents space for resources. The ecological dynamics are limited by single seasonal influxes of resources and subsequent depletion through foraging. A varying number of resource types (species) are modeled and each can have varying degrees of 5 nutrients, bulk and toxicity ($\sum(R_i) + R_{tox} + R_{bulk} = 1$), i.e. all resources have equal unit size.

Resources can be found on the CA grid points and the maximum number of resource items per location is equal to the number of layers. When items are eaten they are removed from the field.

2.2 Individuals

We model individuals which forage in groups using an event-based formalism. Their behavioral repertoire involves moving, searching for food, eating and doing nothing. Furthermore, individuals digest food and learn. Individuals move in a continuous 2D space and can learn during foraging when they find unknown resources. Movements are determined by grouping tendency and food availability.

When modeling foraging we have taken into account that selectivity is an important aspect of primate foraging [12,13]. We model foraging motivation (probability) as a decreasing sigmoid function of an individual's stomach contents. Parameters are set to ensure that an individual's stomach becomes full considerably before digestion has taken place, increasing the importance of selectivity. Furthermore, we model individuals to form estimates of environmental conditions to enable them to adjust their selectivity to changes in the environment. However, the adjustment occurs with sufficient delay to ensure selectivity in a heterogeneous environment. We assume that expectations play a role in primate foraging and believe them to be important for the learning process. For the present model we use individuals that do not evolve, reproduce or die.

Grouping. In contrast to many models of flocking and schooling (e.g. [14]), grouping in our individuals is mediated by foraging. In this way resource availability or distribution can affect grouping. The exact individual motivation for grouping is not important for the model, however our grouping rules are inspired by the idea that primates form groups to avoid predation [15].

We achieve grouping by modeling individuals to require a minimum number of neighbors ($= 3$) within SAFERADIUS ($= 5$). Individuals check for safety with a certain probability and if they are not safe they move towards the largest part of the group. They do this by moving to the nearest neighbor of the fullest of four randomly oriented quadrants about themselves within MAXVIEW ($= 50$). When individuals rejoin the group in this way, they adjust their direction to average group direction.

Foraging. Hungry individuals search for food if they are safe or haven't checked for safety. To avoid crowding, they only search for food if there are no more than a given number of eating neighbors ($= 1$) within REACHRANGE ($= 0.9$). They search within SEARCHRADIUS ($= 2$) and SEARCHANGLE ($= \pi$) in the direction the individual is facing. A random resource location (grid point on CA) within view is chosen and each resource item at that location is assessed for consumption in a random order. Searching stops when an item is chosen, but can continue up to a maximum of 20 items. If this maximum is not reached, searching continues at another random resource location in view. The maximum number of items defines the time constraints for searching during a search event.

If a food item is selected it is consumed in a subsequent EAT event. If in addition it was beyond REACHRANGE, the individual first moves towards it. If no food is selected an individual can use cues from other individuals within NEIGHAWARERANGE ($= 50$) to find food; they move towards the part of the group

where the density of feeding individuals is highest. Otherwise the individual can search again, move forward or do nothing.

Food Choice: Individuals use preferences and a preference expectation to make food choice decisions ($prob = pref_i / pref_{exp}$). Preferences are formed after digestion of a resource (see Sect. 2.3). Preference expectation is updated when a resource with a higher preference than preference expectation is eaten. Preference expectation then attains the value of that preference. If resources are less preferred than preference expectation, preference expectation decays with time. Preference expectation reflects an individual's estimate of the quality of food presently available in the environment. Resources with a negative preference are avoided. Those with preference zero are unknown.

2.3 Digestion

Digestion capacity is modeled as a normalized function over digestion for 5 nutrients (see Sect. 2.1) and a detoxification capacity: $\sum D_i + D_{tox} = 1$. Digestion takes place periodically (every 100 time steps) and the quality of a resource is equal to the energy an individual gains from it:

$$E_r = \sum_{i=1}^5 (R_i D_i) - R_{tox} D_{tox} \quad (1)$$

Total energy over all resources eaten is equal to $\sum (E_r N_r S)$, where N_r is the number of items of resource r eaten and S is a scaling factor.

2.4 Learning

In this model there are two components to learning: (1) eating a novel resource (learn events) and (2) forming resource preferences.

Learn events: Learn events occur when individuals eat unknown resources. This occurs with a fixed probability (PROBEXP (= 0.001)) if there are unknown resources available. The probabilities of learning are encoded genetically and reflect learning propensity. In the current version, learn events depend only on learning opportunities in the environment and not on any previous learning.

Preference Updates: Individuals form and update resource preferences due to a feedback from digestion. Updates are equal to an update factor times the difference between the average energy gained from digestion and the average expected energy (preference) for all resources eaten:

$$Pref_i = Pref_i + (C \frac{S_i}{S_T} (E_{avg} - Pref_{avg})) \quad (2)$$

where S_i is the number of items of resource i in the stomach, S_T is the total number of items in the stomach and C is an update constant.

Since learning resource preferences depends on digestion time intervals, it is a delayed process. It is sensitive to interference when a mixture of resource types is digested simultaneously, because preference updating is averaged over all resources. Feedbacks on preferences from digestion have been shown for rats [16] and primates [17] and interference has been demonstrated in goats [18].

3 Experiments

In this paper we report on baseline experiments where we study individual learning in different environmental conditions by looking at diet development. We compare homogeneous and patchy environments and test the effect of differences in individual learning propensities.

We use a 800 by 800 field with 100 resource types. Field size is hereby large enough to avoid global resource depletion and resource diversity is high enough to allow for divergence of individual diets. For homogeneous conditions, resources are spread evenly, but not all resources are present at each location. For patchy conditions, patches don't overlap and have empty space in between (see Fig. 4). Resources are initialized simultaneously on an empty field at the beginning of each "season" ($= 10^5$ time steps) and are depleted by foraging.

When comparing different environmental conditions we ran simulations with 20 naïve individuals for 3 seasons and observed diet development, behavior and group cohesion. To test for effects of grouping we ran simulations with solitary individuals. When comparing different learning propensities we ran simulations with 20 explorative (neophilic) and 20 non-explorative (neophobic) individuals.

4 Analysis

We visualize and analyze diets using clustering techniques [19] on data matrices of feeding frequency of each individual over all resources. We display dendrograms and sorted data matrices.

On the one hand we cluster individuals to determine which individuals share dietary components and the extent of dietary overlap in a foraging group. On the other hand we cluster resources to determine which resources share patterns of foragers. In the latter case it is informative to compare distributions of feeding over resources with a randomized feeding distribution. For this we randomize individual foraging patterns over resources before clustering. This means that we randomize the feeding distributions of each individual.

For the clustering, Manhattan distances are used. When clustering individuals, we search for groups of individuals with similar diet and use average distance linkage. When clustering resources, we use single linkage focusing on the distance to the nearest resource. If these nearest neighbor distances center around a certain value, this indicates that there is no common preference for any of the resources and that feeding is over-dispersed over resources.

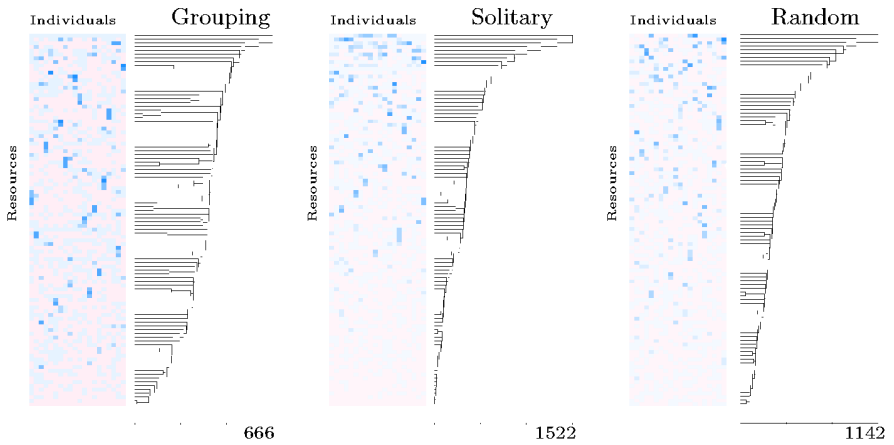


Fig. 1. Dendrograms and data matrices for 100 resources eaten in the 3rd season by 20 individuals in an homogeneous environment: grouping individuals, solitary individuals, and randomized feeding distributions. We use Manhattan distances and single linkage for clustering. Resources eaten by grouping individuals are clearly over-dispersed compared to random and solitary feeding distributions.

5 Results

5.1 Minimal Diet Overlap in Homogeneous Environments

In homogeneous environments we find that foraging groups structure the environment locally through depletion and thereby shape the opportunities for learning. Each individual tends to feed on and learn from resources not eaten by others. Thus each individual develops its own unique diet. This is revealed in cluster analysis which shows that individual diets are over-dispersed over resources types. In comparison, the distribution of resources used by solitary foragers has a closer resemblance to a randomized distribution (Fig. 1).

5.2 Large Diet Overlap in Patchy Environments

In patchy environments we find that foraging in groups has a social influence on individual learning and leads to large within-group diet overlap (group-level diets). In patchy environments foraging groups develop considerably more uniform diets than either solitary individuals in the same environment, or foraging groups in homogeneous environments (Fig. 2 a,b vs Fig. 1). In patchy environments, individuals in groups visit the same patch, therefore any learning taking place is shared with group members. As a consequence, homogenized diets develop.

Diet overlap is not perfect, especially if foraging groups can fragment and each sub-group follows different paths in space. Each sub-group encounters different resources and develops a different diet. However, comparing diets by clustering individuals from separate simulations, results in two main clusters along simulation lines (Fig. 2 c). This illustrates that groups from each simulation form their

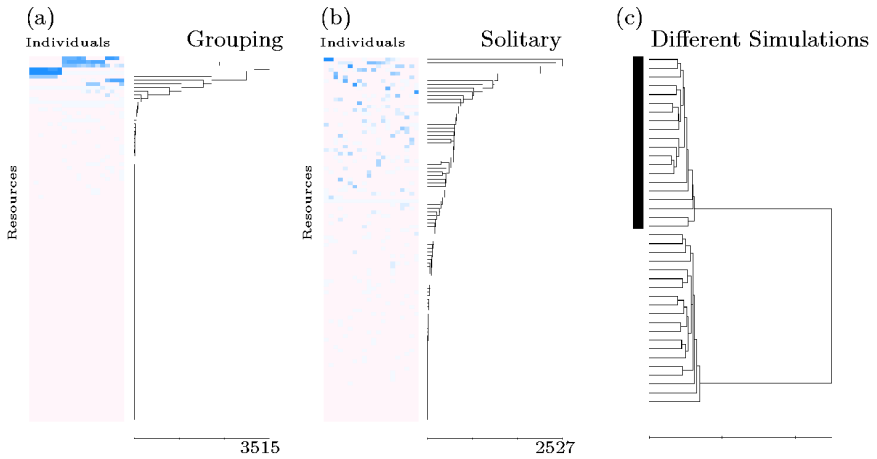


Fig. 2. Dendrograms and data matrices for 100 resources eaten in the 3rd season by 20 individuals in a patchy environment: (a) grouping and (b) solitary individuals and (c) dendrogram showing clustering of 40 individuals from two simulations (black bar indicates one simulation) according to diet. For clustering we use Manhattan distances and single linkage, except for (c) where we use average linkage. Grouping clearly results in homogenized diet development, and groups in different simulations clearly develop their own diets.

own unique diet despite encountering the same number and quality of resources. This implies that grouping in space can shape the context for individual learning, ensuring what is learned is similar to what would be learned under social learning. Thus even without social learning group-based diets emerge.

5.3 Learning Rates, Individual Variation, and Group Cohesion

In previous simulations individuals were identical and our main interest was in environmental differences. Now we study within-group differences in learning propensity (neophobic vs neophilic). Our primary result is that differences in learning cause differences in diet, reducing foraging group cohesion. In turn, diet differentiation is enhanced. How this occurs depends on the environment.

In homogeneous environments neophobia results in better quality diets (results not shown). Neophilic individuals mix more resources while learning and develop less distinguished preferences due to interference during preference updating. This reduces their selectivity during foraging. Being more selective, neophobic individuals move on sooner, thus finding more preferred and better resources and depleting these before neophilic individuals arrive. Neophobia therefore appears advantageous.

Higher movement rates in neophobic individuals brings them to the group periphery. Under present parameter settings this spatial organization does not lead to group fragmentation, but it could under less stringent grouping tendencies.

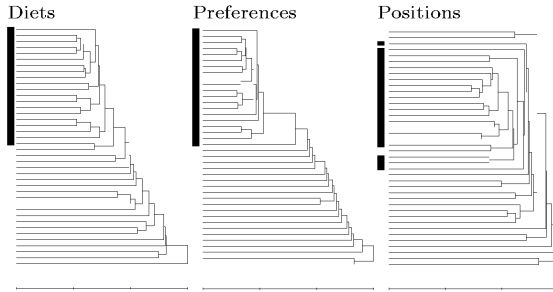


Fig. 3. Dendrograms of 20 neophilic (black bar) and 20 neophobic individuals in a patchy environment clustered on diets (over 3rd season), preferences (at end of 3rd season) and spatial positions (over 3rd season). We use average linkage and Manhattan distances, except for spatial positions where Euclidean squared distances are used. Neophilic individuals are more clustered in all cases.

In patchy environments neophilic individuals develop more homogeneous diets than neophobic individuals. This occurs because neophilia increases the rate of knowledge acquisition and the likelihood of sharing knowledge with group members. As a consequence, neophilic individuals more often stop together at patches. In contrast, neophobic individuals try to move on and end up on the group periphery. This stretches out the foraging group and increases the likelihood of group fragmentation. Fig. 3 illustrates these effects in a foraging group without fragmentation. Neophilic individuals are clearly more similar in diet and resource preferences than neophobic individuals. They are also more cohesive in space, as indicated by the shorter distances between neophilic individuals after clustering on spatial positions. Underlying these results are intricate interrelations between learning, foraging and the spatial organization of a group. This spatial organization shapes learning and foraging opportunities, yet is at the same time a product of differences in learning and foraging interests. This feedback reinforces within-group differences.

In both environments, individual differences lead to group stretching causing stress on group cohesion. In homogeneous environments this occurs because neophobic individuals are more selective foragers. In patchy environments neophobic individuals move to the group periphery because they don't share foraging interests. Whether group fragmentation actually occurs depends on the interplay between the environment and the strength of grouping tendencies. We further tested the effects of individual differences on group cohesion by running simulations with individuals initialized with different diets in a patchy environment. Results show that groups fragment clearly along dietary lines (Fig. 4).

6 Discussion

The results we present are preliminary and reflect only baseline experiments, yet they clearly demonstrate interesting inter-relations between learning, foraging

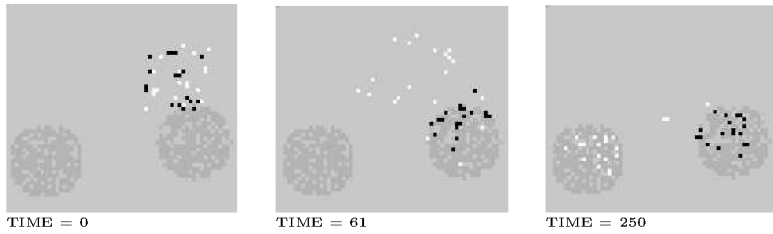


Fig. 4. Snap shots of simulation with 2 diets (black and white individuals have different diets). From left to right: initialization together, splitting due to different feeding interests and eventual feeding on different patches

and an environment with many different resources. In our simulations, resource distributions have a large impact on how diets develop mainly as a consequence of learning opportunities per location and a structuring of the environment through depletion. Depletion leads to a reduction and bias of learning opportunities, but the way this occurs depends on the environment.

Given that competition for resources exists in a foraging group, minimal diet overlap seems a good strategy. As seen above, such diets develop automatically in a homogeneous environment. However, this stands in contrast to the group-level diets that we see in most grouping animals; nevertheless it forms an interesting baseline with which to compare diet development.

In contrast, patches allow grouping in space to assert a social influence on individual learning, resulting in group-level diets. This could be the simplest way to inherit foraging information. However, group fragmentation occurs more easily in a patchy environment and since sub-groups can develop different diets, this leads to diet diversification. Moreover, individual variation within groups stimulates group fragmentation. This is seen for individuals with different diets, but also for individuals with different learning propensities.

Social learning is mostly considered in terms of diet improvement. However, we have seen that individual learning in patchy environments leads to homogenization of diets in a way expected for social learning (see Fig. 2). Moreover, individual variation in learning rates endangers group integrity. Therefore, we suggest an alternative role for social learning, namely that it could be important in reducing individual differences in order to maintain a group's spatial cohesion.

We conclude that insights into the intricacies arising between learning, foraging and environmental conditions are important for understanding learning, diet formation and group cohesion. These intricacies cannot be studied by ethological observation in the wild, foraging experiments, nor by using minimalistic models, however they are demonstrated in the baseline simulations of this artificial world model.

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