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A Genetic Algorithm for Evolution from an Ecological Perspective

Abstract: In the population model presented, an evolutionary dynamic is explored which is based on the operator characteristics of genetic algorithms. Essential modification of genetic algorithms are dynamic boundary conditions and the inclusion of a constraint in the mixing of the gene pool. The pairing for crossover is governed by a selection principle based on a complementarity criterion derived from the theoretical tenet of perception-action mutuality of ecological psychology. According to Swenson and Turvey this mutuality principle is a consequence when evolution is viewed from a thermodynamical perspective. The Second Law of thermodynamics becomes a physical selection principle by which increasing complexity produces an increase in the rate of dissipation. The present simulation tested the contribution of selective recombination. The effect is measured by the rate of energy dissipation, as well as in three operationalized aspects of complexity. The results support the predicted increase in the rate of energy dissipation, paralleled by an increase in the average complexity of the population. The spatio-temporal evolution of this system, i.e. its frequency distribution of changes in population size, displays the characteristic power-law relations of a nonlinear system poised in a critical state.

1. Introduction

In Darwin's account of evolution the central principle for a species' successful adaptation and development is natural selection, a purely *a posteriori* fitness evaluation for randomly created individuals. In search for an *a priori* account to the prototypical question of how a complex dynamical system evolves toward functional efficiency, the theory of complexity has provided a new perspective, largely based on results from molecular biology. Recently Swenson and Turvey[11] adopted a somewhat unorthodox stance, which can be seen as a reaction to Neo-Darwinistic approaches in proposing thermodynamic principles for selection[11,12]. Their argument combines two assumptions: Firstly, in accordance with irreversible thermodynamics, the basic unit is conceived as an open system, embedded in a global system which obeys the Second Law of thermodynamics. Secondly, in allegiance to the central tenet of Ecological Psychology, animal and environment are viewed to form a cyclically related system, in which perceiving and acting mutually condition each other[4,5,9,12]. The relation between perceiving and acting is lawful, and behavior is goal-directed. In contrast to Neo-Darwinist theories which focus on the genetic code as the analytic level of choice, this conceptual framework chooses interactive behavior as the focus of analysis.

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Swenson and Turvey's argument comprises four major steps: (1) Thermodynamic principles, as foremost expressed by the Second Law, are the fundamental laws that govern the evolution of matter in the universe. (2) Highly ordered states, which at first sight seem to defy the development toward final maximum disorder, are factually in concordance with classical thermodynamics, because complex states increase the *rate* of energy dissipation and, hence, entropy production. (3)The way by which matter increases the rate of energy dissipation is the assembly of living matter into higher-order states by way of an active, perceptually-guided behavior. (4) The key unit in this self-organizing process is the dual relation between organism and environment via Gibson's notion of information and the mutual conditioning of perception and action. Information from the environment is determined by the organism's action which, in turn, creates the information.

The following population model applies, in the main, the operators from genetic algorithms, but introduces the notions of open systems and intentional behavior. We start with a brief outline of some assumptions of ecological psychology, followed by the specific goals and the required modifications of genetic algorithms. A numerical experiment will be presented which tests the effects of a goal-directed behavior in the evolution of a population.

2. Some Tenets from Ecological Psychology

In line with irreversible thermodynamics[2,3], the ecological perspective on adaptive behavior, in particular its focus on the perceptual control of movement coordination, emphasizes that biological systems are open and constantly absorb energy from, and dissipate energy to the environment[7]. The central tenet of ecological psychology is that an animal together with its environment constitutes such a dynamical system and is defined over their mutual relation and is not reducible into its two components[11]. The principle of the *mutuality of perceiving and acting* emphasizes that an animal's perception of the environment provides control constraints for the animal's actions, in turn, the animal's actions provide constraints on the perceptual information from the environment. This is referred to as the *perception-action cycle*. In this theoretical framework, the concept of information is reformulated. In contrast to Shannon's concept of information which is a quantity, neutral with respect to its subject matter, ecological information is specific to what it informs about and symmetrically defined over perceiver and environment. Observables are defined for the dual pair of perceiver and environment. The detection of information in the environment controls the behavior, which itself accomplishes the detection of relevant information. Two points will be picked up in the model: (1) The inexorability of goal-directed behavior which is lawfully specified by information, and (2) this information is mutually defined over animal and environment. As a result, organisms evolve toward states of higher complexity, the rate of energy dissipation increases and entropy production in the whole system is increased.

3. Goals of the Model and Definition of Operators and their Dynamics

In the following simulation, some modifications of the original idea of genetic algorithms are introduced, which, in fact, transform the original optimization strategy into an artificial population which displays complex behavior. Foremost amongst these changes is the construction of individual units as open systems, which are characterized by an inflow and outflow of energy. In total, the modifications can be viewed as an emphasis of the deterministic aspect of the model. The major modifications are:

(1) The modeling of bit strings as open systems with energy flow, where inflow and outflow are determined independently.

(2) The notion of random selection of bit strings, where in each generation every bit string can cross with every other string, is replaced by a goal-directed selection of the crossing partner.

(3) The predetermined and static fitness function is replaced by dynamic boundary conditions for the population's development.

(4) The interactions between these open systems and their dynamic environment are governed by nonlinear functions.

In a numerical experiment we want to show that these modifications lead to a behavior, in which:

(1) Evolution towards a higher degree of complexity is achieved.

(2) The rate of energy dissipation on the *global* scale increases with the rising complexity in the *individual* strings.

(3) This state of higher complexity displays the properties of a *critical state* with a power-law distribution in the fluctuations of the population size.

(4) The fractal characteristics, as predicted by the hypothesis of *self-organized criticality*, are more pronounced when the perception-action is included.

To aid the intuitive understanding of the algorithmic operators and parameters illustrative language is frequently chosen to describe the structural ingredients of the model.

Population: The individuals of the population are strings of binary units. These units can be either M (for meat units) or V (for vegetable units). The initial population consists of a random selection of such strings of equal initial length. Each string is attributed a fitness value which is uniformly set for all individuals in the beginning and which will become a function of energy flow and its complexity.

Energy inflow: Energy inflow, or "food uptake" by the individuals, is determined by their present configuration. The minimal requirement for a string to absorb energy is a sequence of adjacent M's or V's. Beyond a minimal length of this "eating block", food of the same type as the block can be eaten. The amount of energy inflow is a weak power function of the actual length of this eating block. Simultaneously, the same quantity of food is subtracted from the respective energy resource. M's are subtracted from the "meat basket" and the stock in the "vegetable basket" is reduced when V's are eaten. To account for the typical dynamic of supply and demand, as known from market economy, an additional nonlinearity governs the increase of the string's fitness value: the greater the supply, the easier fitness can be increased; the lesser the supply, the lesser energy can be added to the fitness balance. Subsequently, the fitness value of each bit string is updated. The length of the strings is not affected by this energy uptake. In the case when one bit string has more than one eating block, of the same or of a different type, its fitness can be increased through all of them. Food depletion, on the other hand, is a linear function of the available supply.

Energy supply: An initial energy supply is provided by the two "baskets" of V's (vegetables), and M's (meat) which are refilled at each iteration. To obtain the nonconstant replenishment, observed in real market situations, the replenishment is scaled by a Gaussian distribution function: If the food supplies are high or low, filling up is relatively low, while in the midrange the replenishment is optimal. This nonlinearity amplifies the situation, when food is scarce and it prevents unbounded growth, when food is available in abundance.

Energy dissipation: The energy inflow is counterbalanced by an energy outflow. This dissipation of energy is determined by the "effort" for the string to find the best mating partner. Thus, energy dissipation is closely linked to reproduction and the goal to improve its offspring's fitness. This is the point where the principle of the perceiving-acting cycle comes into play.

Energy flow on a micro and macro scale: For the individual, food intake and energy dissipation determine a flow through the system, which is monitored by the fitness index. Each flow is governed by different nonlinearities, but there is a balance between energy uptake and consumption. Likewise, on the macro level of the ecosystem, which comprises the total population and the food resources, an energy flow is set up through the replenishment of food and the summative dissipation of energy of all the individuals.

Mating and perception-action cycle: As the fitness index is a function of the ability to eat, which itself is determined by the length of the eating block, a viable search principle must lead to an increase of the length of this homogeneous block. To implement a degree of directedness in the selection of a mating partner, a complementary measure is introduced which attempts to capture information as a dually defined concept. The degree of complementarity is quantified by the Hamming distance, defined as the sum of the differences between the genes at corresponding locations in the sequence (identical genes yield zero, nonidentical genes count as 1). The larger H, the higher the probability that the (double) crossover will replace the units of less favored type. In other words, given its own particular sequence, the most complementary string is selected for crossover. This search, however, is not conducted over the whole population, but only over a subset. The size of this subset is calculated as a linear function of the string's length and its fitness. This takes into account the fact that the longer and fitter a bit string, the larger the subset must be to provide an adequate choice. It also pays tribute to the fact that the higher the degree of heterogeneity, the more choice is necessary to find a matching partner which provides potential improvement. This advantage of a large subset is counterbalanced by the disadvantage that the larger the subset, the longer is the search and the more energy is dissipated. Additionally, the dissipation of energy is proportional to the string's length. As a result, the subset together with dissipation is a nonlinear function of string length.

Consequently, energy outflow is the price the organism has to pay for a higher probability to increase energy inflow in the next generation.

Mating and crossover: Unlike the Mendelian view, the pairing for the crossover is not random, but is directed by the individual's intention to increase the chance of survival. As fitness is a function of the ability to eat, i.e. the length of the eating block, a viable search principle must lead to an increase of the length of this homogeneous block. In a first step, a partner for crossover is selected according to maximal Hamming distance. Then double crossover, instead of single crossover, is used to provide an operation that optimizes the possible gain from the selected partner. To strike a balance between chance and self-directed improvement, the two points of crossover remain random. Each string can partake in crossover only once per iteration.

Mutation: Stochasticity is incorporated at two instances. Firstly, the biological principle of mutation is instantiated as the flipping of a single bit. In the situation when the population of individuals has settled on an equilibrium with predominantly meat-eating or vegetable-eating population, random mutation becomes the source for change when the respective food resources are depleted. It also acts as a disturbing factor to the goal-directed development. Secondly, mutation can change the length of a genome. Longer genomes have a higher chance to assemble a sizable eating block, but also dissipate more energy in the pairing process. Hence, as the advantages of eating ability and dissipation are counterbalanced.

Reproduction: Reproduction is not linked to crossover, but is independently regulated by the fitness index. When the fitness index reaches a critical threshold, duplication of the genome occurs. The two identical offspring then start with half of the parent's fitness value.

Extinction: Reproduction is counterbalanced by extinction. When the fitness value decreases to zero, the string dies. As reproduction and extinction are defined individually, this leads to overlapping generations.

4. A Numerical Experiment

The pivotal point of the present endeavor is an evaluation of the role of a purposive search principle in the restructuring of components, in particular its effect on the system's entropy production and degree of complexity obtained by the system's individuals. According to Swenson and Turvey's hypothesis, the perception-action principle is a necessary constituent to obtain an increase in the rate of entropy production and increase in complexity. Extending these suppositions we also expect that the system’s spatial and temporal variables satisfy the characteristic features of a system at its critical state[1]. In particular we anticipate power law relations with an exponent between -1 and -2.

Method

The population experiment was run with two conditions. The first condition includes the perception-action principle, referred to as the "Perception-Action-Run" (P-A-run). In the second condition the selection of mating partners purely follows chance, and will be called the "Random-Search-Run" (R-S-run). All other parameters and relationships are kept the same. For each condition 25 runs over 10,000 generations were performed.

Operationalization of complexity (C) and entropy production (EP)

Complexity: To express complexity in a single quantity poses practical and theoretical problems. To set apart our approach, based on combinatorial and probability considerations, from more philosophically grounded definitions, the measure will be called heterogeneity. Possible candidates are absolute length, the proportion of M's and V's in the sequence, and the number of alternations from M to V within one string. The complicating factor is the theoretical requirement that complexity, viz., heterogeneity should correspond to fitness, as well as constitute a fairly improbable state. For instance, when looking at the number of alternations alone, the maximal number does express maximal heterogeneity, but it is not the most improbable state. The most probable state lies between an uninterrupted sequence of alternations and absolute homogeneity, and the probability follows the binomial distribution. A subsequent comparison with the binomial distribution can therefore give an estimate of its probability. Absolute length also has to be considered, because the way energy dissipation is defined makes it directly proportional to absolute length. Rather than forcing these aspects into one quantity, we opted to leave these interrelations transparent and use three separate measures to describe heterogeneity:

1) Absolute Length: L = number of bits in the string.
2) Relative number of alternations: $A_{rel} = A / A_{max}$ (with $A_{max} = L - 1$).
3) Relative content of M's or V's : $M_{rel} = M / L$, or $V_{rel} = V / L$.

Rate of entropy production: Within the confines of the model it seems viable to operationalize entropy production with the total energy dissipation of the individuals. The rate of change in the entropy production ΔEP is calculated from the average change in energy dissipation per generation ΔE_{diss} over the number of individuals (N):

$$\Delta EP = \Delta E_{diss} / N$$

Self-organized criticality: To test for the predictions of self-organized criticality the summative measure of population size N_{pop} and its change was chosen to capture the dynamic of the different effects. For the operationalization, N_{pop} was registered every 10 generations and the consecutive measures were subtracted. The data points were binned and displayed in a histogram. The exponent of the power function was obtained from the double-logarithmic plot, in which the slope of the linear regression yields the exponent.

Parameters: The experiment was conducted with the following parameters: initial population (100), initial string length (10), initial fitness index (6.0), initial food supply (300/300), food replenishment (50 per iteration, multiplied by a Gaussian being a function of the current food supply), minimal length for an eating block (5), reproduction threshold (15), crossover rate (50%), mutation rate for bit flip (.005), mutation rate for length change (.00002).

5. Results

Two exemplary time series in Figure 1 and 2 illustrate the behavior of the population over 2000 iterations.

FIGURE 1 Example of temporal evolution of meat and vegetable eaters in the population

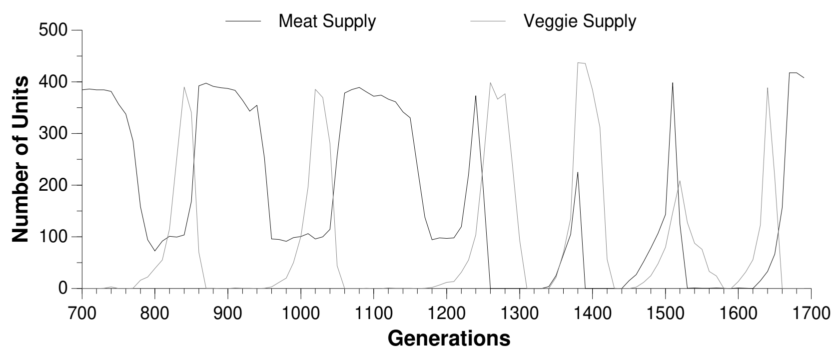

FIGURE 2 Example of temporal dynamics of meat and vegetable supplies.

Heterogeneity: Figure 3 shows the time evolution of absolute length L of the strings. In a P-A-run the length increases markedly after about 2000 generations and rises by three bits to approximately 13 bits. It increases further, however, very slowly. In a R-S-run length L increases after 1000 generations, but then clearly stays below the value obtained in the P-A-run. The second measure of heterogeneity is the average number of alternations in the sequence A_{rel}, and is displayed in Figure 4. It starts from the value 0.5, the highest probable number according to the binomial distribution, and decreases throughout the evolution. In contrast to length L, it does not show a significant difference to the runs with random search, and is therefore not separately shown in the Figure. This decrease in both conditions indicates the trend toward more homogeneity.

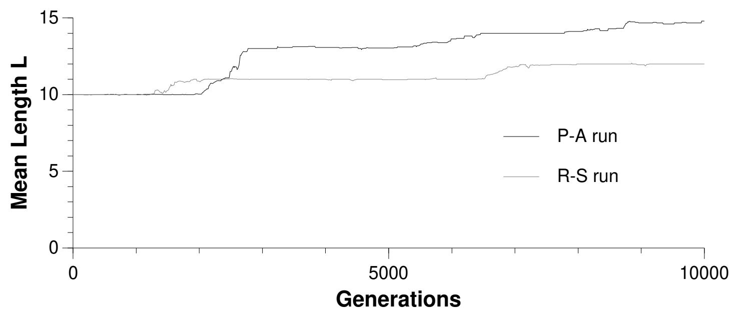

FIGURE 3 String growth over time for P-A and R-S runs

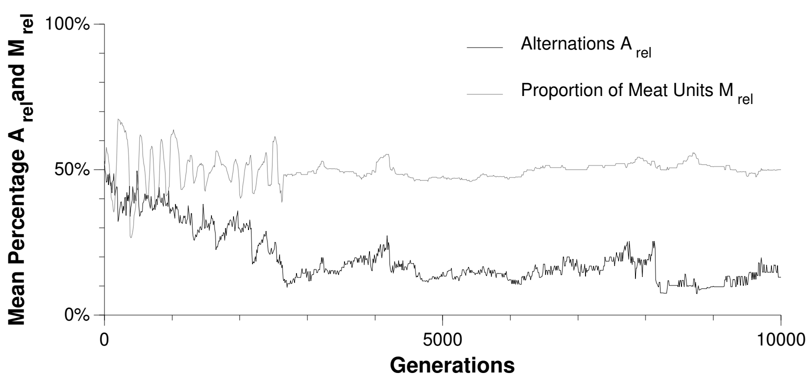

FIGURE 4 Change of alternations A_{rel} and proportion of meat units M_{rel} over time

The relative proportion of meat and vegetable units, M_{rel} and V_{rel}, the third measure for heterogeneity, fluctuates around the value 0.5 in both conditions and shows no significant trend.

Rate of entropy production: In Figure 5 the rate of energy dissipation is plotted for both conditions. The dissipation rate visibly rises with increasing generations and the difference between the two search principles is evident for these exemplary runs. The average slopes (not shown in graph) of the linear regression over 10,000 generations is 3.46 x 10^{-6} in the P-A-run, whereas in the R-S-run it is 1.84 x 10^{-6}. The confidence intervals only slightly overlap.

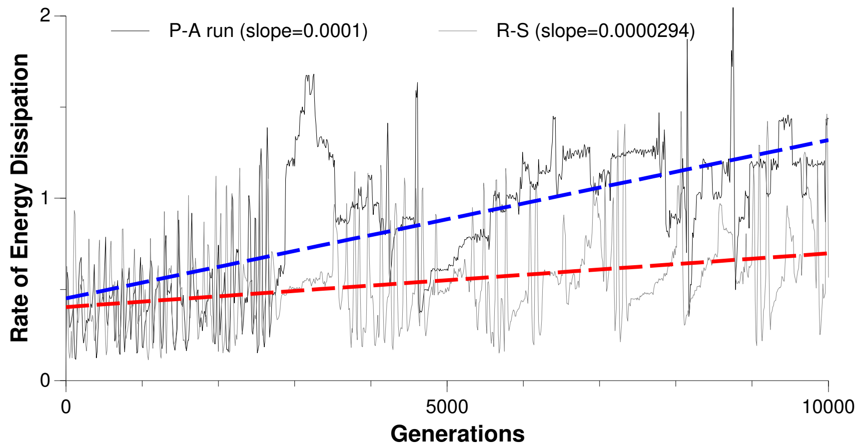

FIGURE 5 Energy dissipation over time for the P-A and the R-S runs

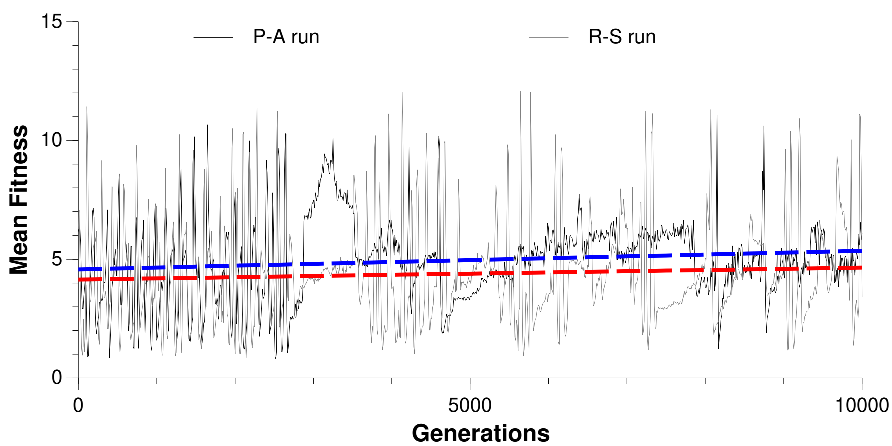

FIGURE 6 Comparison of mean fitness over time between P-A and R-S run

Fitness: The fitness index is graphed over 10000 generations for the two runs in Figure 6. In both conditions the average fitness value starts from 4.5 points and reaches approximately 5.0 points, which is quasi-constant. The value shows fluctuations with a gradual approach of its ceiling of 15.0 points, where reproduction sets in, followed by a lapse back onto a lower level. It is noticeable that in the P-A-run this oscillating dynamic spans about 100 generations, whereas in the control condition it only stretches over about only 50 iterations.

Self-organized criticality: For the determination of the power-law function, the data of the 25 runs of one condition were pooled to provide an adequate number of data points. The change in population size between at every tenth generation was recorded and grouped into integer bins. Their normalized frequency is plotted in Figure 7. The logarithmic plot is approximated by a linear regression. The slope of -1.76 in the P-A-run conforms to the hypothesized slope between 1 and 2 at the critical state ($r^2 = .93$, $p < .0001$). For the R-S-trials the plot is slightly more convex, but the linear approximation is still significant ($r^2 = .93$). The range in which the linear approximation is satisfactory is also larger for the P-A-runs than for R-S-runs.

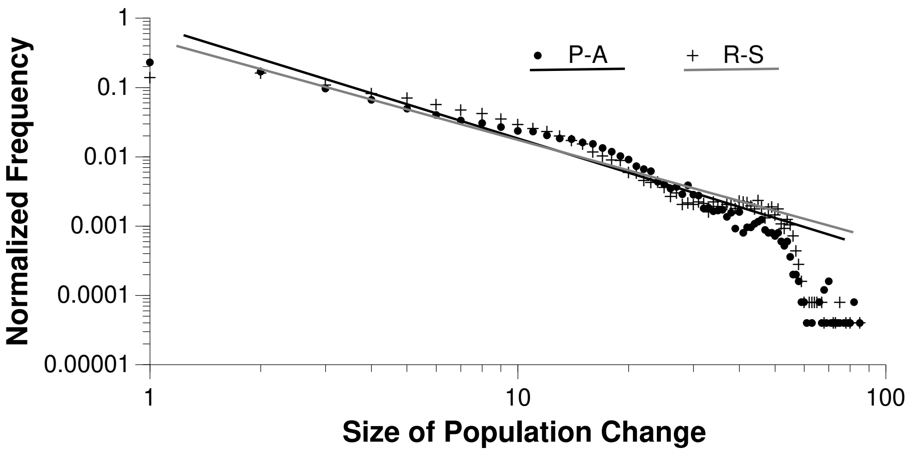

FIGURE 7 Power law fit for the size of population change over all P-A and R-S runs

6. Discussion

To date, genetic algorithms have followed the Mendelian view on genetic transmission and rested on random crossover, i.e. individuals contact one another by mass action alone. The present model was inspired by an advance made by Swenson and Turvey and includes the element of information-constrained behavior, thereby cutting short pure probabilistic considerations. Such informational constraints were implemented for the "choice" of crossover by using a complementarity criterion defined over two individuals. The simulation experiment compared the evolutionary dynamic of a population where an active search principle was implemented against conventional random-search. The results yield a clear evolutionary advantage for the P-A-runs. The major phenomenon is the increase in the rate of entropy production as hypothesized by Swenson and Turvey. Further support and some explanation for this effect comes from the simultaneous increase in heterogeneity of the individuals. Looking at the three operationalized measures, the results showed that, while the relative proportion of alternations and the relative proportion of M or V units show no difference, string length grows significantly more with the intentional component than without. These findings together suggests that the P-A condition favors a chunking into eating blocks, which then leads to a higher inflow of energy, and, consequently, to an increase in fitness. Fitter and "more complex" individuals have a better chance of adaptation, but this also entails a longer search and more energy dissipation. Here the link between energy dissipation and complexity is established. It is still noteworthy, however, that it is the rate measure which is sensitive to the active search principle.

The constant fitness average in both conditions is no real surprise. According to the reproduction rule fitness rises to the threshold of 15 points and then lapses back to half of its value. As the average is also influenced by weaker strings, the value fluctuates around 5 points. More interesting is the oscillation pattern: In the P-A-condition the cycles stretch over approximately 50 generations, compared to 100 generations in R-S-runs. This can be interpreted as a more vehement dynamic in the experimental condition, in the sense of a stronger tendency and readiness to change, or adapt. Hence, the dynamic in the fitness value can be interpreted as an indicator for the "fluidity" of the state[8]. A quantitative analysis of the fluctuation pattern is in progress.

The results of heterogeneity measures also point at another aspect of this dynamical system: the stratification into a micro and a macro level and the competition between the "goals" on the micro and the macro scale. On the level of the individual, the P-A target is greater homogeneity in composition, because homogeneity ensures the ability to eat and increase fitness. The long-term disadvantage is that the species cannot change between meat- and vegetable-preference so readily and become prone to extinction, when supply of their respective food becomes low. Heterogeneity, on the other hand, ensures greater adaptability and exploitation of the available food resources, but keeps the energy inflow at a lower level. This discrepancy between the local, short-term goals, and global, long-term advantages is captured in the size of population, which expresses the balance between extinction and reproduction, and where reproduction is the product of the gain in fitness. In order to evaluate the balance between short-term advantage and long-term adaptability, the data were tested for their 1/f properties predicted by the theory of self-organized criticality. When adaptability is the balance between the readiness to change and more conservative properties, or between short-term profits and long-term precautions, the present population reflects this as the trade-off between the increase in eating-blocks and over-reliance on one food resource. Both aspects are captured in the size of the population which is the balance between extinction and reproduction. In both conditions the data of the change in population size could be significantly approximated by a power-law relationships. When the complementarity criterion guided the reshuffling of the "genes", the exponent was slightly more negative than in the control condition, but the regression fit provided no basis for a differentiation between the two conditions, although qualitative inspection shows more curvilinearity in the R-S-runs. In the P-A trials, however, the linear fit stretches over a wider range. This latter result allows the tentative conclusion that the active search favors the organization to a critical state. More variables will be tested to consolidate this conclusion.

Acknowledgments

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