Co-evolution of cognitive strategies and the environment

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Abstract

In this paper we focus on the cognitive costs that are involved in more reasoned decision-making strategies. We argue that a lower investment of cognitive effort may be beneficial both for the individual as for the sustainability of the population as a whole. We further argue that the most effective distribution of decision-strategies will be related to the stability of the environment people live in. Hence personality factors that determine the preference for a certain distribution are subject to evolutionary pressures. Experiments with a simulation model show that sustainability can be reached when cognitive costs are included in the model. Moreover it is being demonstrated that evolutionary pressures favour a mix of cognitive strategies. Finally we demonstrate that an unstable environment favours the development of a smaller population investing more cognitive effort in their decision making process.

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Introduction

The main puzzle in the study of commons dilemmas is to understand why people so often do not overharvest their resource. Hardin (1968) makes the traditional perspective that individuals sharing a common resource are trapped in a tragedy famous, but this line of thought goes back to the Greec philosopher Aristotle. Formal models from economists, assuming selfish agents, predict the overharvesting of the resource. However, numerous laboratory experiments and field studies have been performed during the last decades and they show that overharvesting does not occur always (e.g., Ostrom, 1990; Bromley et al., 1992; Ostrom et al, 1994, Dawes et al, 1977; Jorgerson & Papciak, 1981; Yamagishi, 1988).

There are two lines of research studying this phenomenon. Political science is studying the self-organisation of institutions, analysing the importance of trust, reciprocity, communication, sanctioning and monitoring (Ostrom, 1999). On the other hand, psychology is studying the characteristics of the individuals and groups. Factors that have been studied are group size, pay-off structure, communication, identifyability, group identity, personal restraint, uncertainty, expectations of other person's behaviour, trust, social value orientation, personality factors, personal responsibility and morality (see e.g., Jager, 2000). In this paper we will focus on the cognitive costs associated with decision making process, thus following a psychological approach.

The core question we address in this paper is how the cognitive costs of decision making affect harvesting in a commons dilemma. If the maximising agent from standard economic theory is not capable of avoiding this tragedy of the commons, whereas real people often are, it can be assumed that cognitive costs may have a positive effect on the sustainable use of common resources. Most of the time people do not use a maximising strategy in deciding what (or how much) to consume, but rather they save on cognitive effort and use some kind of heuristic. To allocate our limited cognitive capacity over all decisions we have to make, we have a wide spectrum of decision strategies at our disposal. In some situations we spend lots of cognitive effort in making a decision, e.g., when buying a house. In other situations we seem to act automatically, for example during our daily shopping. Not only the amount of cognitive effort differs among decisions, also the extent to which we use information on the behaviour of other people differs among our decisions. Sometimes we simply imitate the behaviour of our friends, parents, colleagues, or even the general (cultural) trend of a country. For example, when buying clothes we usually conform ourselves to other people. In other situations our decisions are more individually based, such as buying a refrigerator.

Two main features emerge from the broad spectrum of decision strategies: automatic versus reasoned behaviour and individual versus social processing. These two dimensions can be condensed into four different decision strategies: repetition, imitation, social comparison and deliberation. In our previous work we designed a general framework of what we think are the main decision strategies (Jager, 2000).

The question is why we need a spectrum of different strategies. If deliberation is a very effective decision strategy leading to the best possible solutions, we may expect that it will out-compete the other strategies. This is not likely to be happening since there are different costs for different decision strategies. Reflexes do not cost cognitive resources, but deliberation does. Therefore, deliberation will reduce the possibility of making other decisions. Furthermore, other humans can benefit from the cognitive efforts of a deliberating person by copying his/her behaviour. Hence, there may be an evolutionary advantage to using a mix of the different cognitive strategies.

In the literature on the evolution of cognition (e.g., Boyd & Richerson, 1985; Richerson & Boyd, 2000) there is the argument that climatic instability during the pleistocene would have required a larger adaptive capacity to survive. Unstable environments, where natural disasters occur more frequently and it is harder to survive, would have benefited the smarter people, and hence stimulated the evolution of cognitive processes and learning. This would have favoured the development of a larger brain, despite the fact that this larger brain requires substantial energy from our metabolic system. Richerson and Boyd (2000) state that learning will only be favoured when environments are variable in time or space in difficult to predict ways. Social learning in their opinion is a device for multiplying the power of individual learning.

The same argument may hold for the development of the personal factors that determine the tendency of people to engage in a certain distribution of cognitive processing. We hypothesise that people in a less stable environment have an evolutionary advantage when they engage more in reasoned processing. In our research we thus do not focus on the biological evolution of cognition and the capacity for learning, but rather focus on personality characteristics that favour certain types of cognitive processing.

Two main factors that determine the preference of people to engage in one of the four basic types of cognitive processing are aspiration level and uncertainty tolerance. Aspiration level and uncertainty tolerance thus (partly) determine the mix of cognitive strategies a person is likely to employ. We assume that aspiration level and uncertainty tolerance are related to (partly) heritable personality characteristics, which makes them prone to evolutionary selection. Aspiration level relates to the level of need satisfaction that they aspire for to be satisfied. A high aspiration level is assumed to be a manifestation of wisdom, objectivity, knowledge and reflection, which are relevant factors in the Intellect factor of the Big five personality structure (Goldberg, 1990). A high uncertainty tolerance is assumed to be a manifestation of self-assurance (poise) and self-reliance, and a low anxiety and insecurity, pole factors of the Emotional Stability (neuroticism) factor of the Big five personality structure.

Loehlin, McCrae, Costa and John (1998) studied the heredity component of the Big five personality structure using twins. They showed the Big Five dimensions to be substantially and about equally heritable, with little or no contribution of shared family environment. Jang, Livesley and Vernon (1996) found that broad genetic influence on the factor Emotional Stability (neuroticism) was estimated at 41%, and on Intellect (conscientiousness) 44%.

As far as we know there are no studies that report how personality characteristics affect population dynamics. Hence there are no empirical data confirming our hypothesised evolutionary selection of aspiration level and uncertainty tolerance. In animal studies, experiments have focussed on heretical pro-active and reactive coping styles in populations of mice, showing that the population size and proportion of pro-active (aggressive) mice are interrelated and, often fluctuate (e.g., Koolhaas et al., 1999). Studies like these suggest that population dynamics of humans may also co-evolve with distributions of personality characteristics. In another vein, results showing that the distribution of personality characteristics differ over different cultures (e.g., Mastor et al, 2000; Mak & Tran, 2001; Pulver et al, 1995) also indicate that population and personality characteristics are related. One study (Steel et al, 1997) suggests that there exists a relation between personality structure and the environment people prefer to live and work in.

In this study we thus take the cognitive repertoire of people as a stable fact, and focus on how the environment affects the aspiration level and uncertainty tolerance of people. Our hypothesis is that a mix of decision strategies is an efficient mechanism to allocate the limited cognitive energy over the decision problems to satisfy our needs. Moreover we hypothesise that a certain aspiration level and uncertainty tolerance will have an evolutionary advantage, and that a population will grow towards these levels over several generations. We further hypothesise that a more unstable environment would require more adaptive capacity to survive, and hence will favour agents having a high aspiration level that engage more in deliberation. Furthermore we expect that an unstable environment favours a lower uncertainty tolerance, as social learning may be most effective in unstable environments. Finally, we hypothesise that unstable environments have a smaller carrying capacity. Stated bluntly, we hypothesise that the evolutionary (dis)advantage of certain personality characteristics depend on the stability of the environment. We will test these hypotheses by using a digital perti dish, a computer simulation model. This model is an artificial world where agents consume energy from the ecosystem. Each time-step these agents have to make decisions among movement and the amount of harvesting. In this model we can experiment with different assumptions on cognitive processes and costs of cognitive processing to identify the cases in which the system does not collapse.

The main argument for not overharvesting the common resource is the development of social norms in the group of appropriators. Norms concerning the appropriate behaviour in a situation can emerge through social learning by imitating the behaviour of the peers, and in that sense can be conceived as a cultural evolution. Richerson and Boyd (2000) stress the importance of social learning in this context. In this paper, their are no explicit social norms, but agents can imitate behaviour of their neighbours as a result of social processes. As we will show in this paper, the mere assumption of cognitive costs is sufficient to produce sustainable agent behaviour, without making it possible to include explicit social norms in the model. Before we discuss the simulation model, we will elaborate on the decision making process of people, as this is the theoretical rationale behind the simulation model.

Decision making

In their daily life people employ different strategies to meet the many different decision problems they encounter. As already mentioned before, people may spend more or less cognitive effort in making a decision, and may use more or less social information in their decision making. The critical question is how people decide on which decision strategy to employ in a given situation. The work of Simon (1955, 1959, 1976) on bounded rationality offers a perspective on why habits and complying with a norm may be a rational thing to do. The essential argument is that humans optimise the full process of decision-making (*procedural rationality*), not only the outcomes (*substantive rationality*, Simon, 1976). This holds that consumers may decide that a certain choice problem is not worth investing a lot of cognitive effort, whereas another choice problem requires more cognitive attention. The less important a decision problem is, the less cognitive energy one is willing to invest in the decision, and hence, the simpler the decision heuristic that will be employed.

Often people use their own previous experiences in a heuristic. For example, when people are satisfied with a certain decision, they may not waste any cognitive energy on decision making the next time, but perform automatic behaviour. However, people may also employ the behaviour and experiences of other people in their decision making. This becomes clear when, for example, observing fashions in clothing. It appears that the cognitive strategies that people employ can be organised on two dimensions: (1) the amount of cognitive effort that is involved, and (2), the individual versus social focus of information gathering.

Regarding the **first dimension**, amount of cognitive effort, the basic idea is that people allocate their limited cognitive capacity over various decision problems they face so as to maximise their utility. When one is frequently being confronted with the same or similar decision tasks and the previous behaviour yielded satisfactory outcomes, it is a good strategy to economise on cognitive effort by using simple heuristics or a habitual script in making the decision. This allows for allocating most of the cognitive capacity to decision problems that require more attention in order to find a satisfactory solution, such as non-routine decisions with important consequences. Because cognitive processing takes time, using simple decision heuristics will save time. This explains why people tend to use simpler decision heuristics when under time pressure (e.g., Smith, Mitchell and Beach, 1982; Wallsten and Barton, 1982; Wright, 1974; Ben Zur and Breznitz, 1981). Also when the decision is less important (in terms of consequences) the decision-maker may use a simpler heuristic instead of using all information available (e.g., Tversky, 1969; 1972). The simplest type of behaviour in terms of cognitive effort refers to preconscious habits (Fiske and Taylor, 1991), i.e., behaviour that bears a reflex like character.

Regarding the **second dimension**, the individual versus social focus of information gathering, especially uncertainty is the key-factor that determines the focus of the information search process. When people are certain of themselves, they usually refer to their own previous experiences when making a deliberate or automated decision. When uncertain, people may use the experiences of other people to come to a decision in a cognitive efficient manner. Especially the behaviour of other people with about similar abilities may provide a useful clue in the decision making process. Simple imitation may be an economical way of allocating cognitive capacity to a decision. The *Social Learning Theory* (Bandura, 1977; 1986) states that seeing someone else's behaviour being reinforced may affects one's own behaviour. This imitating however requires more cognitive effort than a simple habit, because one should be *attentive* to the behaviour of someone else, *understand* and *remember* that behaviour, being able to *reproduce* that behaviour, and experiencing *reinforcement* after performing the behaviour yourself (Bandura, 1977). The Social Impact Theory (Latané, 1981) is also relevant in the context of social information gathering. It states that the social influence of group A over group B is a function of strength of source A (status, power, ability etc.), the proximity of A and B in space or time, and the number of source persons A available. The basic idea is that these are the factors behind processes of innovation and conformity, where conformity refers to effects from a majority on a minority, and innovation as an effect from a minority on a majority. Following simple norms can also be considered as a social focussed heuristic that requires relative little cognitive effort. However, according to the *Theory of Planned Behavior* (Ajzen, 1985, 1988, 1991), the *subjective norm*, may require more cognitive effort in making a decision. The subjective norm here refers to a person's perception of the opinion of others about him/her performing the relevant behaviour. The subjective norm is proposed as a function of one's *beliefs* that referents think whether the person should or should not perform the behaviour (called the injunctive norm), weighted by the *motivation to comply* with those referents. Social comparison (Festinger, 1954) is a key process here, involving that people consciously compare their opinions and abilities with those of other people. These comparisons follow dimensions such as the possession of material goods, financial means, status, principles, attitudes and skills. With respect to opinions, people have a drive to roughly conform to others. With respect to abilities, people have a drive to be (somewhat) superior to others. Becoming aware of a subjective (social) norm would involve an assessment of relevant others and an appreciation of their behavioural intentions, which involves considerable more cognitive effort than simple imitation or obedience to a simple norm.

In organising the various decision strategies that people employ, we find it instructive to use the two dimensions as graphically depicted in Figure 1.

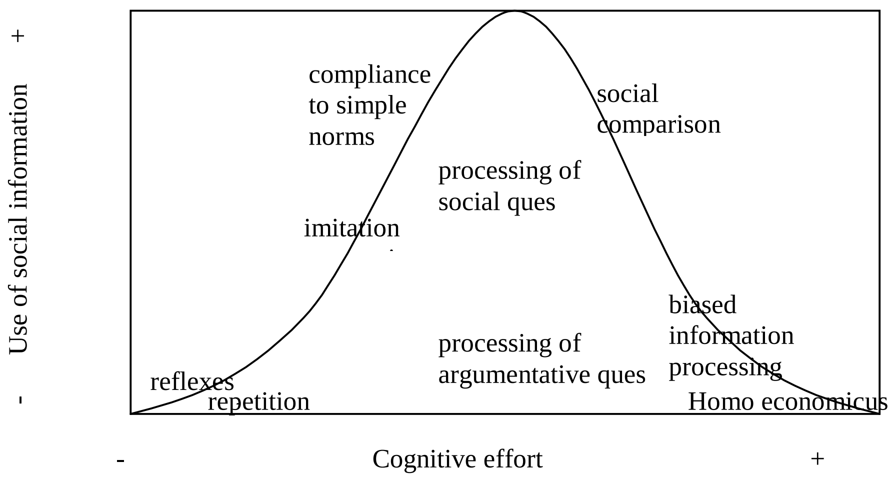

Figure 1: Different decision processes organised along the dimensions of cognitive effort and use of social information

Figure 1 shows that decision strategies that hardly require any cognitive effort (reflexes), or require very much cognitive effort (the prototypical homo economicus) do not use social information. Strategies that require an intermediate cognitive effort may use both social and non-social information. Here, uncertainty is a key factor that determines the degree to which social information is being used in the decision making process.

In organising the decision strategies along these two dimensions, a perspective emerges regarding how people differ regarding their abilities and motivations to invest cognitive effort in a decision, and to what extend they use social information. Hence, this perspective contributes to the understanding of heterogeneity between people as regards their decision making. For example, some people may be more inclined towards using social information, and other people may have a larger cognitive ability, making it easier to invest cognitive effort in the decision making process. On top of that, understanding how these abilities and motivations may change in a repeated decision making situation, provides a perspective on how people switch between decision strategies over time, and hence contributes to the understanding of heterogeneity within people. For example, when people become more uncertain, they will be tend to use more social information in their decision making, and when people are not satisfied, they may be inclined to spend more cognitive effort in their decision making process as to find a better behavioural opportunity.

To test hypotheses regarding the effects of heterogeneity in the decision making process on collective outcomes we developed the consumat approach. This approach involves a multi-agent simulation model of decision-making processes. In the next section, we will shortly elaborate on the consumat approach.

The consumat approach

The consumat approach as introduced by Jager *et al*. (1999, see also Jager, 2000) is based on the comprehensive conceptual model of choice and decision making behaviour as discussed in the previous section. As such it tries to offer a more psychological based meta-theory of human decision making than the frequent used ‘rational actor’ approach. Figure 2 shows how the various factors in the consumat approach are being organised in a conceptual model. Opportunity consumption is defined in a broad sense, including issues like material goods and services. The consumat approach considers basic human needs and uncertainty as the driving factors behind the human decision making process. The consumat approach can be considered to be a generic tool that may be employed when formalising human decision making in a multi agent model.

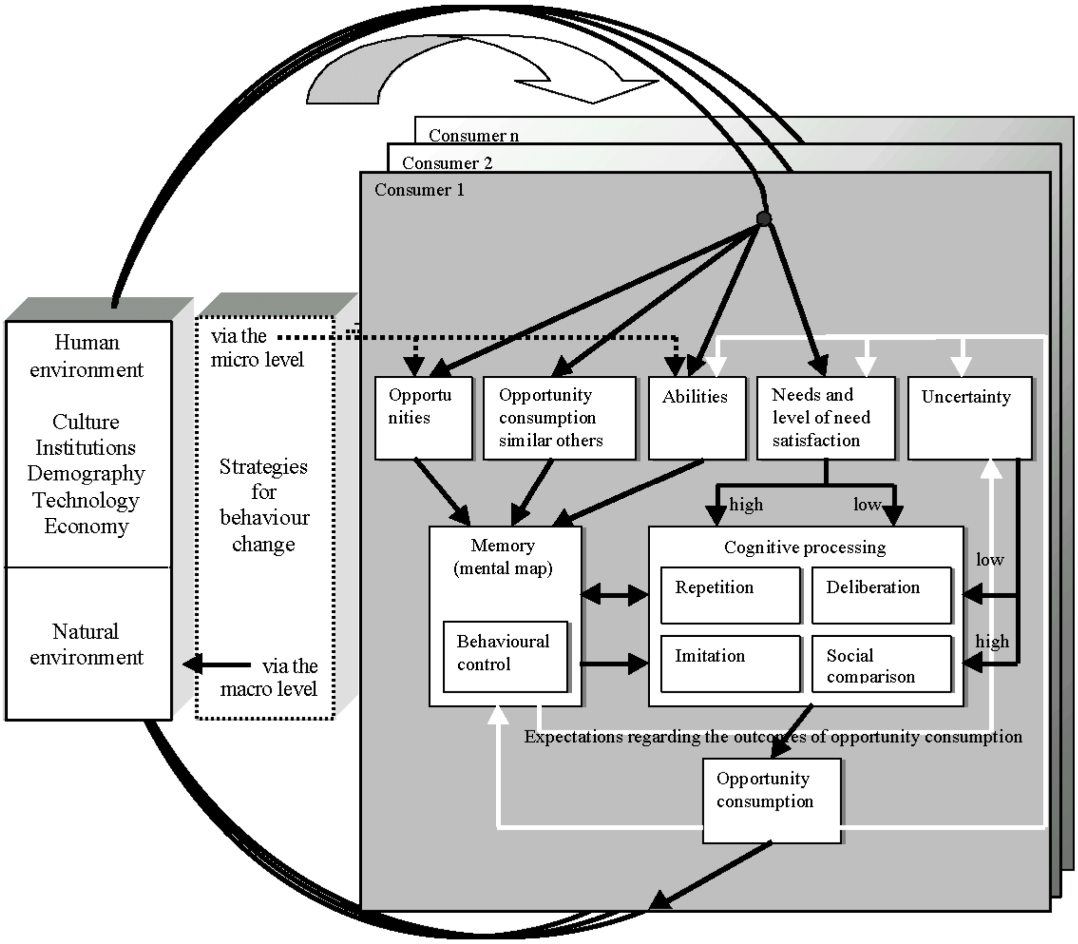

Figure 2: The conceptual model of consumer behaviour for n consumers

Whereas the specific formalisation of the simulated agents, called ‘consumats’, may differ over various circumstances, all these formalisations are built on the same structure as schematised in Figure 2. The driving forces at the collective (macro-) and the individual (micro-) level determine the environmental setting for consumat behaviour. This may be represented by a collective resource. The individual level refers to the consumats, which are equipped with needs which may be more or less satisfied, are confronted with opportunities to consume, and that have various abilities to consume opportunities. Furthermore, consumats have a certain degree of uncertainty, depending on the difference between expected and actual outcomes of their behaviour.

The consumats may engage in different cognitive processes in deciding how to behave, depending on their level of need satisfaction and degree of uncertainty. Consumats having a low level of need satisfaction and a low degree of uncertainty are assumed to *deliberate*, that is: to determine the consequences of all possible decisions given a fixed time-horizon in order to maximise their level of need satisfaction. Consumats having a low level of need satisfaction and a high degree of uncertainty are assumed to engage *in social comparison*. This implies comparison of its own previous behaviour with the previous behaviour of consumats having roughly similar abilities, and selecting that behaviour which yields a maximal level of need satisfaction. When consumats have a high level of need satisfaction, but also a high level of uncertainty, they will *imitate* the behaviour of other similar consumats. Finally, consumats having a high level of need satisfaction and a low level of uncertainty simply *repeat* their previous behaviour. When consumats engage in reasoned behaviour (deliberation and social comparison) they will update the information in their mental map, which serves as a memory to store information on abilities, opportunities, and characteristics of other agents.

After the consumption of opportunities, a new level of need satisfaction will be derived, and changes will occur regarding consumats' abilities, opportunities and uncertainty. Moreover, the resource will change, thereby affecting the consumption in subsequent time steps.

The model

The ecosystem

The model consists of a two dimensional grid, wrapped in both axes to derive a torus and to avoid edge effects. Each cell represents a renewable resource that can provide energy for the agents. At the start of a run, the initial size of each resource is set to a uniform number between zero and a fixed maximum X_k. At each time step the energy level of the renewable resource X increases according to a logistic growth curve:

$$\Delta X = r \cdot X \cdot (1 - X / X_K) \qquad (1)$$

where ΔX is the growth of the resource per time step and r the logistic rate of growth.

Agents

Agents can reproduce and can die. This all depends on the accumulated energy level. Every time step an agent uses energy, depending on its activities (moving and eating). When agents eat (or harvest the renewable resource), energy is accumulated. When the accumulated level of energy exceeds a certain threshold, the agent produces offspring in an asexual manner. In fact, the agent is split in two, where each copy of the agent has half the energy level of the parent agent. With a small probability, an element of genetic information is not a copy of the parent agent, but a random value. Agent specific genetic information consists of the level of uncertainty tolerance and the aspiration level. When the energy level of an agent drops below zero, the agent will die and leave the system.

The neighbours are defined by a so-called Moore neighbourhood which includes cells to the north, south, east and west of the centre cell as well as diagonal cells to the north east, north west, south east and south west. These always form a square pattern. So a cell has 8 neighbours, and a neighbourhood contains of 9 cells. Assuming a radius larger than one can enlarge the neighbourhood. For example, a Moore neighbourhood of radium two consists of 25 cells.

Each time step the agents make decisions on movement and eating. They move and eat to derive satisfaction of their needs. Whereas in the conceptual model (Jager 2000) we make a distinction between 9 needs on the basis of the work of Max-Neef (1992), in the model we formalise three types of needs, respectively the need for subsistence, the need for identity and the need for belongingess. These three needs appear to be relevant in this context, whereas limiting the number of needs to three keeps the simulation results transparent for analysis and interpretation.

Need for subsistence

The need for subsistence relates to the nutrition that the agent needs to survive. The satisfaction of the subsistence need is formalised as the accumulated energy level. The satisfaction of the subsistence need is implemented as the energy level relative to the maximum energy level, leading to a value between zero and one.

$$N_S = (\frac{E}{E_{\max}}) \tag{2}$$

Need for identity

The need for identity relates to the preferred outcome distribution between the own and the other agents' outcomes regarding energy level. The need for identity can manifest itself in different manners, depending on social orientations such as competitiveness, individualism and cooperation. In the basic model we will only formalise the competitive interpretation of identity, thereby representing Festinger's (1954) idea that people prefer to have more ability than others. Agents want to have more energy than the average level of the whole population. The satisfaction of the identity need is represented with an index, which denotes the agent's energy level compared to the average energy level.

$$N_I = \exp(-\frac{E}{E_{avg}}) \tag{3}$$

Need for belongingness

The need for belongingness relates to the desire of people to belong to a group. This has been formalised as the agents having a preference for being together, instead of being alone in physical space. The satisfaction of the belongingness need is represented with an index, which divides the number of agents in the neighbourhood by the number of possible neighbours, that is the number of cells representing the neighbourhood. The radius of the neighbourhood is assumed to be two. The more neighbours in the neighbourhood, the more satisfied the agent is with respect to its belongingness need.

$$N_B = \frac{\# agents \subset neighbourhood}{\# cells \subset neighbourhood} \tag{4}$$

The total need satisfaction of the agent is a weighted multiplication of the satisfaction level of the three different needs:

$$N = N_S{}^{\alpha} \cdot N_I{}^{\beta} \cdot N_B{}^{(1-\alpha-\beta)} \tag{5}$$

Uncertainty

Uncertainty relates to the fluctuations in outcomes the agent experiences. Uncertainty is formulated as the standard deviation of the individual energy consumption during the last 10 time steps. When there is a lot of fluctuation from time to time in the intake of energy, the standard variation, and hence the uncertainty increases.

Whether an agent becomes satisfied or not, or uncertain or not depends on the threshold levels N_{min} and U_{max}. N_{min} represents the level above the agent is satisfied, and hence functions as an aspiration level. U_{max} is the level of uncertainty it tolerates before becoming uncertain.

We distinguish four cognitive processes in determining eating and moving decisions.

Repetition

When an agent is satisfied and certain it simply repeats its previous behaviour. In this artificial world, this means that an agent continues eating when there is more energy left on occupied cell. When the agent is satisfied, but energy of the local resource is not sufficient to meet the metabolic needs of the agent, it moves to a nearby cell that has the most energy. During one time step, an agent can eat as well as move, as repetition does not require cognitive effort. This is possible in the case the agent eats, and recognises that not sufficient energy is left over for the following time step.

Imitation

When an agent is satisfied and uncertain it imitates the behaviour of nearby agents. The nearby agents are defined as the ones that occupy cells in the Moore neighbourhood with radius 4. When there is enough energy on the occupied cell to meet minimum metabolic energy needs, the agent will eat. The percentage of the resource the agent will harvest is equal to the average percentage of the neighbours. When after this harvest, the energy left over is sufficient for another round, the agent stays, otherwise it moves to the empty cell with the highest energy level.

Deliberation.

When the agent is dissatisfied and certain, it will engage in deliberation. As deliberation costs a lot of cognitive effort, the agent can only eat or move while deliberating. First it will deliberate on whether to move or to eat. This is the balance between satisfying the minimum level of need satisfaction with a minimum level of metabolic costs. If just eating some of the resource of the occupied cell can satisfy the agent, it stays. Otherwise it will move. When it has decided to eat, it determines the percentage, which is necessary to satisfy the needs. When it has decided to move, it will move to that empty cell which will lead to the highest level of expected need satisfaction.

Social comparison

When the agent is dissatisfied and uncertain it will engage in social comparison. Due to the cognitive effort associated with social comparison, the agent can only eat or move. First it will determine on whether it will move or eat in a similar way as in deliberation (taking into account percentage of similar neighbours). But instead of analysing all possible harvest percentages, the agent will base its behaviour on the eating behaviour of the neighbours. In determining how much to eat, the agent will weight the eating fraction of similar others more than that of dissimilar others (weighted average). Similarity is focussed on the aspiration level of the agents, and is formalised as the difference between the values of N_{min} of the agents. After determining the weighted eating fraction, the expected level of need satisfaction is estimated and compared to continuing the existing level of need satisfaction. If copying the strategy of similar others improves the level of need satisfaction this strategy is adopted, otherwise, the strategy of the previous time step is repeated.

Experimental set-up

The model is implemented in CORMAS (Bousquet et al., 1998; http://cormas.cirad.fr) which is a shell around the objective oriented language Smalltalk. CORMAS[1] is especially designed to simulate agents in a cellular automata environment. Parameter values as used for the model are given in Table 1.

The theoretical maximum sustainable population can be calculated. The resource growth is maximal for X equal to 5, and provides 0.5 units of energy per time-step. For 900 cells this equals 450 units of energy. An agent can not survive staying at one cell, and has to move around. When agents move each time step, the maximum sustainable population is equal to 112.

Table 1: Default parameter values.

	Parameter	**Value**
Resource	Grid size	30x30
	Logistic growth rate r	0.2
	Maximum size X (X_k)	10
Agents	Initial population size	40
	Metabolic rate (eating only)	2
	Metabolic rate (moving)	4
	Energy level offspring	100
	Probability mutation	5%

In the experimental design we vary several variables. The first factor we vary is the cognitive costs attached to moving. In the default condition it is not possible to move and eat at the same time when engaging in deliberation or social comparison. This condition represents the cognitive costs condition. A second condition is created in which there are no cognitive costs attached to deliberating and social comparison. This condition functions as a benchmark, making the cognitive-costs-effect visible.

A second factor we vary is the cognitive processing style of the agents. Three conditions are created. The first condition is the *Homo Economicus* (HE), which engages exclusively in deliberation, thereby representing the rational agent from standard economic theory. The second condition is the *Homo Psychologicus* (HP), which employs all four decision strategies. For the *HE* conditions the values of N_{min} and U_{max} are set at 1 so that the agents only deliberate. In the *HP* condition, the values of N_{min} and U_{max} are 0.2 and 0.5 respectively, so that all four cognitive processes can be used. In the third condition we also formalise the *Homo Psychologicus* (HP), only this time we do not use fixed values for N_{min}, but we formalise a distribution of N_{min}. This allows for experimenting with evolutionary processes concerning the fittest aspiration level in the population.

As a sensitivity test we will test the implications for the results when one of the three needs is not incorporated in the analysis. After that, we will experiment with different settings for the (in)stability of the resource. This involves formalising more or less frequent occurring periods of high or low growth. Next to that we will experiment with the evolution of cognition.

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[1] CORMAS stands for Common-pool Resources and Multi-Agents Systems

Simulation Results

In this section we will discuss the simulation outcomes for the various conditions.

Fixed values of N_{min} and U_{max} with and without cognitive costs

First, a number of experiments have been performed with fixed and equal values of N_{min} and U_{max}. Four runs are depicted in Figure 3 where each run has a different combination of N_{min} and U_{max} {(1,1) or (0.2, 0.5)} and assuming cognitive costs or not.

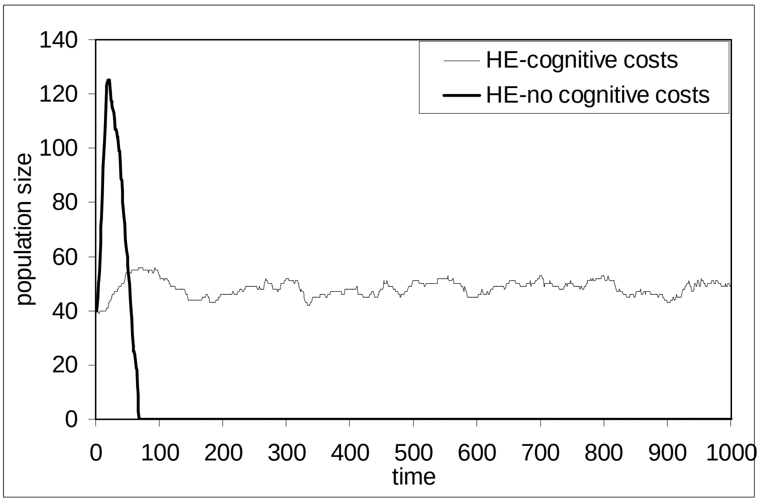

Figure 3a: Population size of 4 runs for homo economicus with and without cognitive costs.

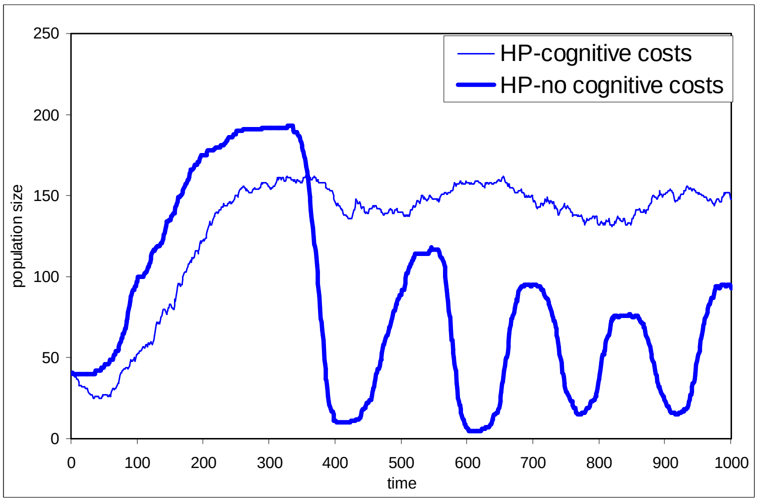

Figure 3b: Population size of 4 runs for homo psychologicus with and without cognitive costs.

In the *Homo Economicus* condition (N_{min} =1 and U_{max} = 1, Figure 3a) the agents will only deliberate and thus will maximise their level of need satisfaction each period. When there are no cognitive costs the agents will eat each cell with a maximal eating rate (99%) and move to a neighbouring cell. Since the fast accumulation of embodied energy, the agents will derive a large number of offspring, but since the resource is overharvested, a typical overshoot and collapse is occurring. In the cognitive costs condition the agents can only eat or move. This reduces the ability to eat rapidly the resource and accumulate energy to generate offspring.

The resulting population size varies around 50 agents, which is lower than the potential number of agents since the resource is harvested beyond the optimal level.

In the *Homo Psychologicus* and no cognitive costs condition the system ends up in cycling behaviour of overshoot and collapse (Figure 3b). The reason is that an increasing population lead to scarcity of the resource, the agents start reasoning and increase their harvesting which accelerates the collapse. During the recovery, the population growth is to fast to fully recover from the crash.

In the cognitive costs condition the population increases up to 150 agents, and the energy biomass is slightly below the optimal level of 4500. The eating rate grows to about 40% resulting in a situation where most agents perform automatic processes of moving and eating simultaneously.

Variable values of N_{min} *with and without cognitive costs*

In the third cognitive processing condition we equip the population with a variety of N_{min} and the possibility of mutation during offspring. The value of U_{max} is put on such a high level that agents only repeat or deliberate (Figure 4). For both conditions (with and without cognitive costs) 25 simulation runs have been performed. During these simulations, the value of N_{min} in the population change leading to an evolution of the typical agent. If there are no cognitive costs involved, the value of N_{min} increases to the maximum value. This is caused by the fact that agents with a higher level of N_{min} aim for a higher level of need satisfaction resulting in higher eating rates.

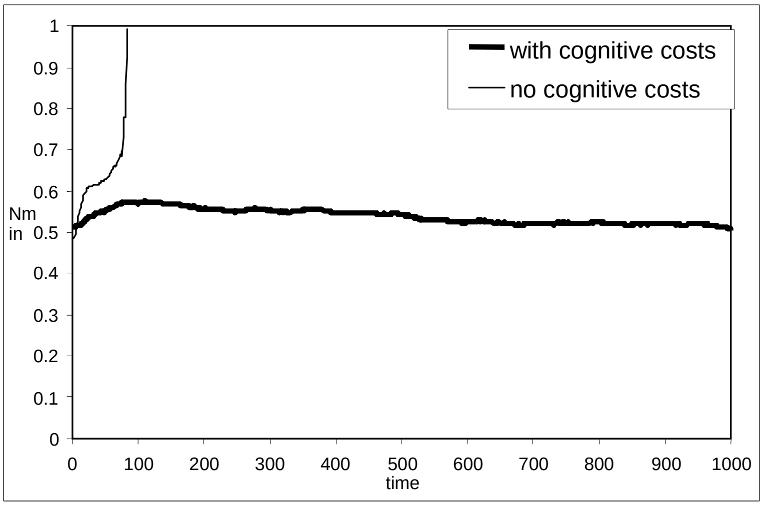

Figure 4: The average value of N_{min} *of the populations for 2 experiments of 25 runs where agents can only perform individual cognitive processes.*

Higher eating rates lead to higher embodied energy and higher offspring. But the evolution of agents with a high aspiration level leads to a collapse of the system due to their over-consumption of the resource (Figure 5).

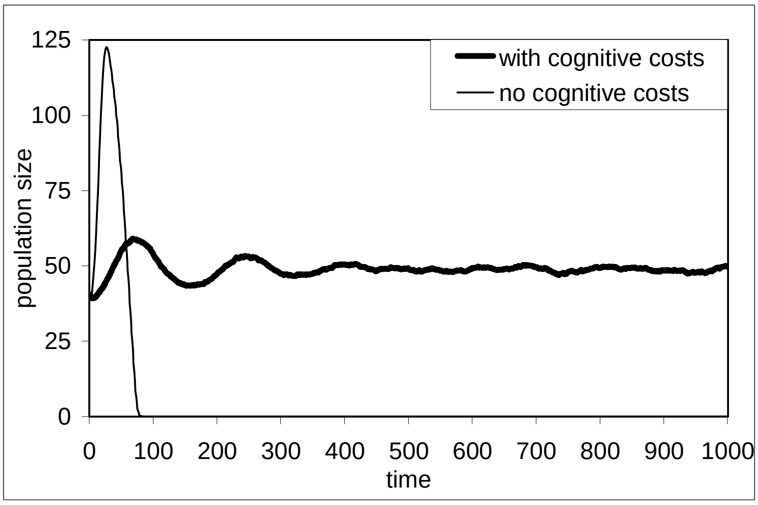

Figure 5: The average population size for 2 experiments of 25 runs where agents can only perform individual cognitive processes.

When cognitive costs are included, the value of N_{min} does not change significantly from the initial values. Since an agent is born with an initial eating rate of 10%, deliberation will cause an increase in the eating rate of the young agents. Agents having a low N_{min} will not deliberate that soon, and are likely to die because of malnutrition (low energy level). Due to the costs of deliberation, a high N_{min} also has no evolutionary benefit, and hence the average value of N_{min} stabilises, just as the population size.

Variable values of N_{min} and U_{max} with cognitive costs

In the next condition both N_{min} and U_{max} evolve. Since now many different processes start to interact, we want to provide some insights in the dynamics of the model, and therefore first discuss a typical simulation run (Figure 6).

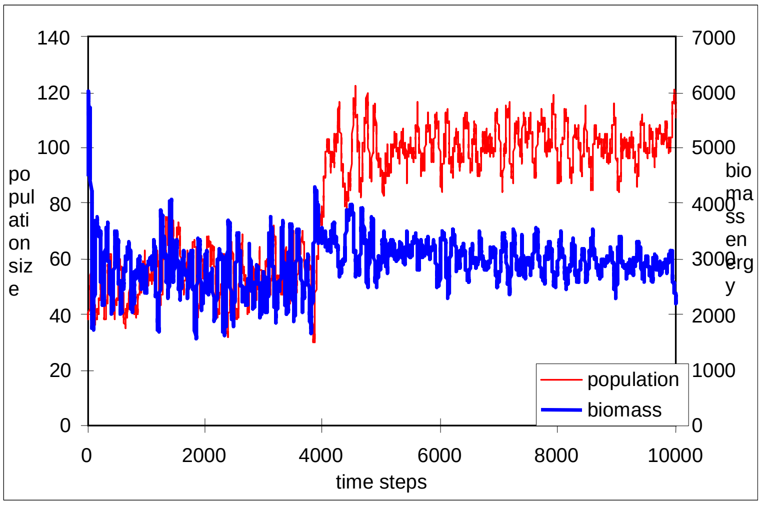

Figure 6: Population and biomass for a typical run where agents can use four different cognitive processes and reasoned behaviour costs time.

The population fluctuates first between 40 and 70 agents. The eating fraction of about 90% is relatively high, leading to local scarcity of the resource and a high fraction of reasoned behaviour. Just beyond 4000 time-steps, enough agents use an eating fraction of around 60%. This enables the agents to form habits (repetition), causing them to stop using cognitive energy for reasoning (deliberation and social comparison). Once enough agents start to repeat and imitate a well-performing eating rate, more agents start to copy this behaviour when becoming uncertain. Since deliberation only occurs when the resource is scarce and there are no large fluctuations in harvesting, the habitual behaviour at a lower eating rate causes the system to become more stable. As a consequence, deliberation as a cognitive strategy will have a very small share in the distribution of cognitive processing, and hence the meme of a high eating fraction disappears from the population. This leads to a lock in into an attractor domain of agents with low aspirations and rather uncertainty tolerant (Figure 7).

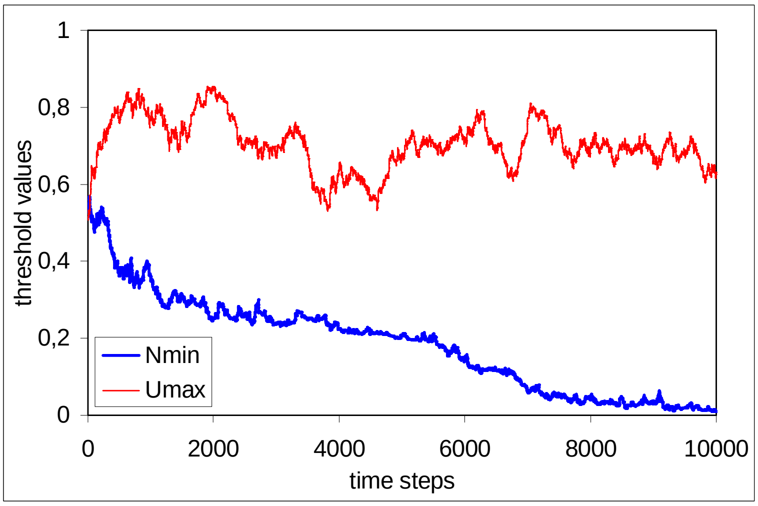

Figure 7: The values of N_{min} *and* U_{max} *of the typical run.*

The average N_{min} of the population decreases, which means that the targets set by the agents become more modest leading to lower consumption rates when deliberating. The uncertainty tolerance slightly increases. Evolutionary pressures favour agents with a lower aspiration level (less greedy) that become less quickly dissatisfied. This had two major advantages. First, greedy agents tend to harvest more before becoming satisfied. Second, when agents are easier satisfied, they spend less cognitive costs.

The mix of cognitive processes in Figure 8 shows that the whole cognitive repertoire is being used, with the highest share by imitation. Imitation can still promote overconsumption of the resource (Jager et al., 2001), therefore the population level and the energy biomass cycle around in the attractor domain instead of reaching an equilibrium.

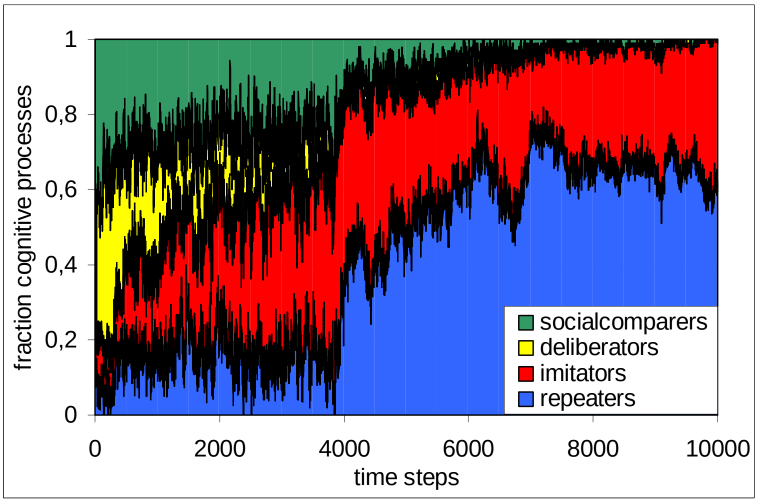

Figure 8: The distribution of cognitive processes of the typical run.

Such a typical run provides shows what dynamics are possible in the model. Performing a larger number of simulations confirms this lowering of $N_{min.}$ Apparently, this stable environment provides an evolutionary advantage to agents that have a relative low N_{min}. The agents become easily satisfied, and start to move and eat each time step since they mainly imitate and repeat. This can only happen when the eating fraction of the imitating and repeating agents is low enough to avoid overharvesting.

Variable values of N_{min} and U_{max} without cognitive costs

When the agents can deliberate/socially compare and move at the same time, the population growth is much faster during the initial cycle, but the population falls deeper when resource scarcity hits the system (Figure 9).

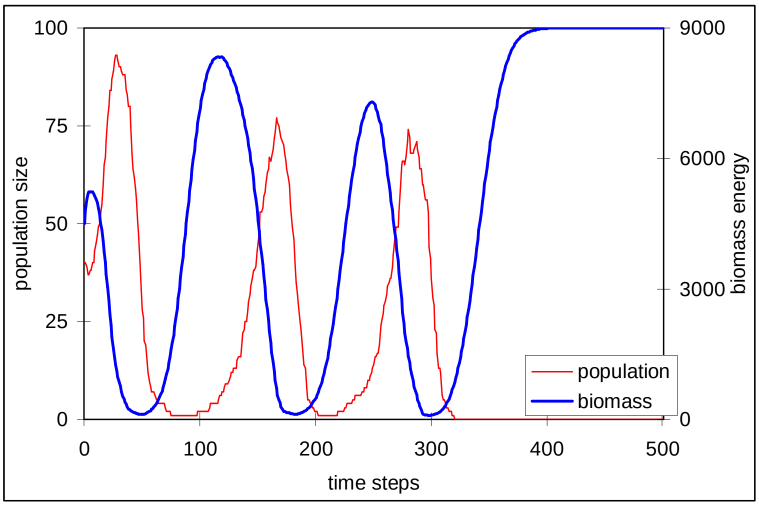

Figure 9:a prototypical run without cognitive costs

Figure 9 shows a prototypical run, where the population collapses due to overharvesting. These overshoot and collapse dynamics are caused by the fact that greedy agents can consume and multiply without constraints until the resource is depleted. In this case, a minimum number of agents survive a collapse, leading to additional cycles. Performing a larger number of simulation runs showed that there is variation in the time of collapse.

In Figure 10 it can be seen that in the cognitive costs condition N_{min} evolves from 0,5 to close to zero, whereas in the no cognitive costs condition N_{min} evolves to a value of around 0,75. Interestingly, uncertainty tolerance is not a factor that makes the crucial differences for the two conditions.

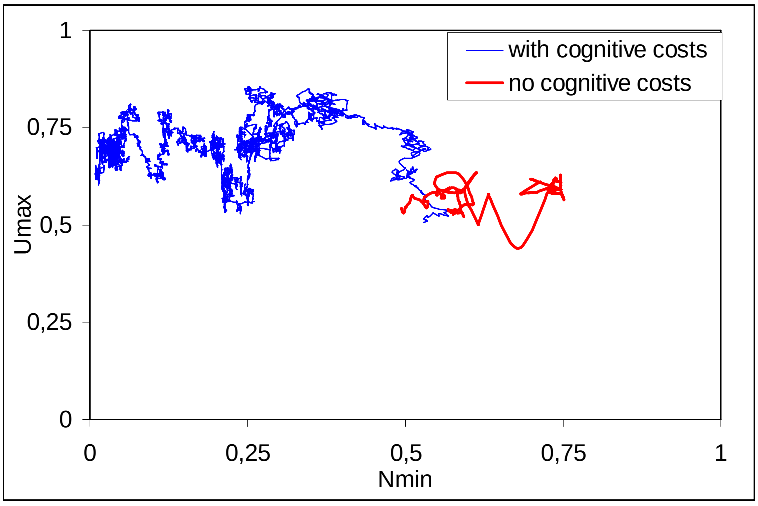

Figure 10: Values of U_{max} and N_{min} for 2 different experiments

Sensitivity test: experimenting with fewer needs

In the default experiments the agents balance the satisfaction for three needs. Now we will explore what happens when one of the three needs is being excluded from the analysis (Figure 11). For the rest we replicate the experiment with cognitive costs and evolving N_{min} and U_{max}. When the need for subsistence is left out of the definition of need satisfaction (alpha = 0), the population size increases significantly. The reason for this is the fact that agents remain valuing energy indirectly via the need for identity, but the need for belongingness is weighted relatively more in comparison to the default experiment. Therefore, the agents spend more effort in being together than in harvesting, causing less overharvesting and a larger population.

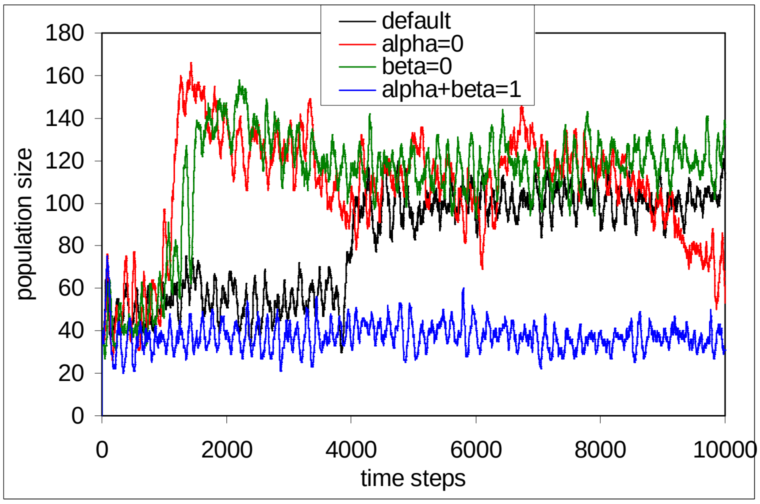

Figure 11: Sensitivity test for fewer needs

When the need for identity is left out of the analysis (beta = 0), the population size also increases significantly. Because the agents no longer compete for the highest energy level, the driving force behind this keeping-up-with-the-Jones's effect is neutralised, causing that more energy is left allowing sustaining a larger population.

Finally, leaving out the need for belongingness (alha + beta = 1) reduces the population size as compared to the default experiment because now only needs aiming at energy are included. As a consequence, the agents eat more, and hence the carrying capacity of the system becomes lower.

Experimenting with unstable growth rates of the resource

The previous experiments have explored the system behaviour in a situation where the growth rate of the resource was stable (20%). The question is how occasional disasters and periods of abundance, translated as a periodical low or high pulse in the resource growth rate, affects both the evolution of aspiration level and uncertainty tolerance, as well as the population that is being sustained. In this experiment, we contrasted a stable situation for 10.000 time steps with situations where every 1000 or 100 time-steps the growth rate of the resource is 3% (a disaster) or 40% (abundance) during 25 time-steps. These values are chosen to keep the average growth level of the resource close to the default run. Figures 12 (which is figure 7), 13 and 14 respectively show the development of N_{min} and U_{max} for a stable growth rate, a pulse every 1000 time-steps and a pulse every 100 time steps.

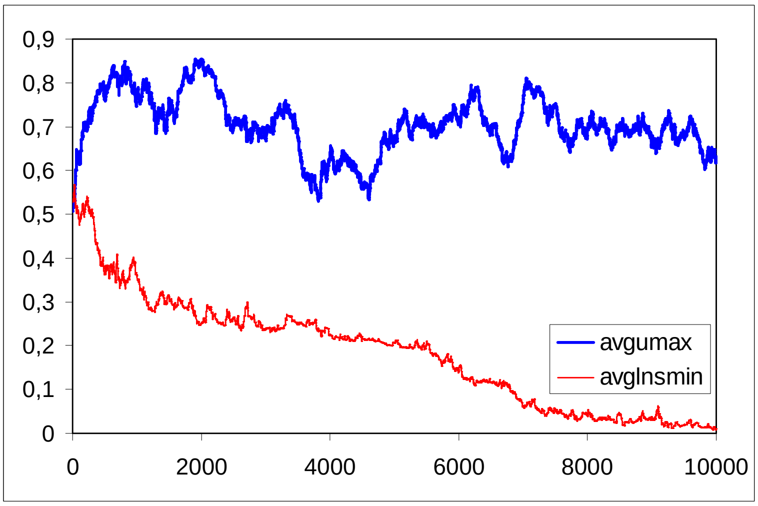

Figure 12 (= 7) The development of N_{min} and U_{max} for a stable environment

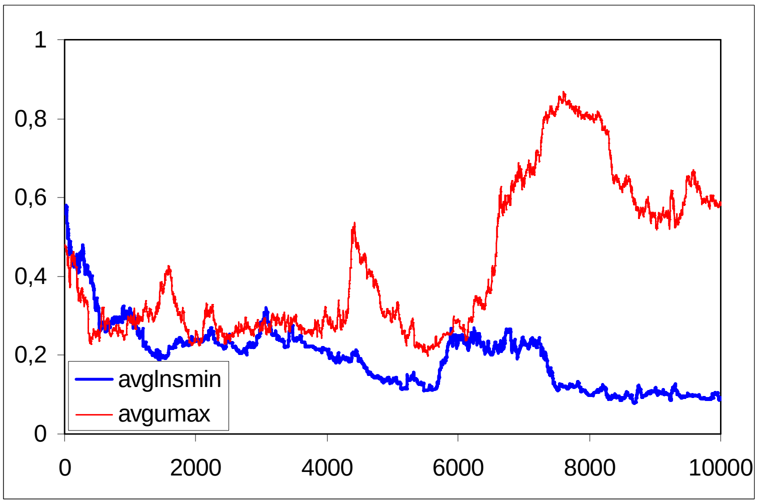

Figure 13: The development of N_{min} and U_{max} for a pulse every 1000 time-steps

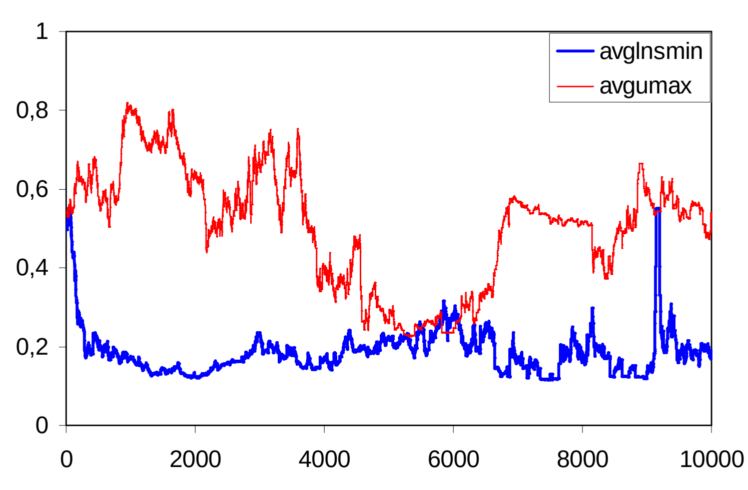

Figure 14: The development of N_{min} *and* U_{max} *for a pulse every 100 time-steps*

What can be observed is that the value of N_{min} increases the more unstable the environment is. This confirms our hypotheses as stated in the introduction. It appears that a more unstable environment requires more adaptive capacity to survive, and hence will favour agents having a high aspiration level that engage more in deliberation. As regards U_{max} it appears that the uncertainty tolerance drops the more unstable an environment is. Apparently social learning is especially efficient when an environment is unstable. This is in line with the argument of Richerson and Boyd (2000) that learning will only be favoured when environments are variable in time or space in difficult to predict ways, where social learning is considered to multiply the power of individual learning. However, whereas Richerson and Boyd focus on the (long term) evolutionary growth of cognitive processing (learning), our experiments focus on the (shorter term) evolution of aspiration level and uncertainty tolerance as key factors behind the distributive use of fixed (non evolving) cognitive strategies.

When we observe the population size in the three environmental stability conditions, we see that the more unstable the environment, the smaller the population that is being sustained. (Figure 15)

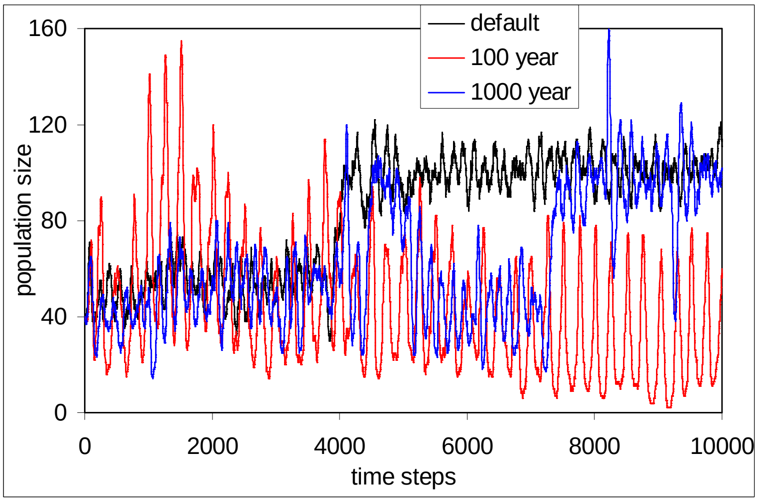

Figure 15: The population size for the three environmental instability conditions

It can also be observed that the more unstable environments elicit much more fluctuations in the population size. This is due to the fact that a more unstable environment favours agents with a higher N_{min} which engage more in deliberation. These agents are more likely to overharvest the resource, especially during a low growth period. On the contrary, during a high growth period their aspiration level causes them to be more successful and yield more offspring. These results are in line with the hypotheses that the more unstable the environment, the smaller and more fluctuating the population is.

Whereas it is clear that an unstable environment causes the population to become ‘smaller and more ambitious’, it is unclear how social learning (imitation and social comparison) affects the population. Therefore we replicate the no pulse and every 100 years a pulse conditions without social learning (only deliberation and repetition). Figure 16 shows that without a pulse the population remains at a level of about 50, which is considerably lower than in the comparable condition with social learning (Figure 15). Apparently, in a stable situation social learning helps to spread the optimal behaviour, whereas in the no social learning condition the satisfied agents remain repeating their previous behaviour.

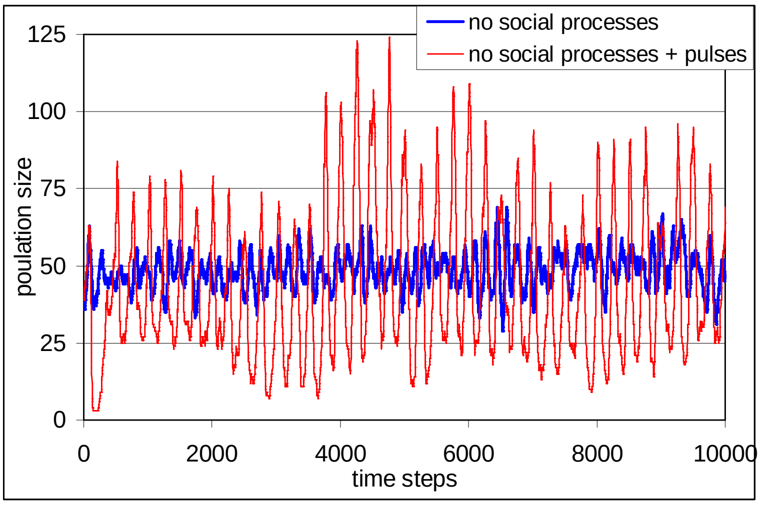

Figure 16: Population size for social processes versus no social processes situation.

Looking at the no social learning - pulse condition we do not observe an interpretable difference between the no social processing and social processing (Figure 15) conditions. This is not in line with our expectations. However, it may be an artefact of our model, as social comparison and deliberation costs the same amount of energy in the model, whereas in reality it is assumed that social learning saves on cognitive costs.

Discussion

These results give a first insight in how cognitive decision strategies and associated personality factors may evolve as a function of the environment. The results suggest that the development of social norms is not an absolute prerequisite to prevent the resource from collapsing. The cognitive costs involved in reasoned decision making causes that people optimise the full decision situation or procedural rationality (Simon, 1976), not only the outcomes. This process causes that a lower aspiration level yields the highest outcomes, and thereby decreases the environmental pressures.

The results also demonstrate that there is a relation between the behaviour of the environment, the population that is being sustained and the cognitive effort the agents invest. These results are in line with the hypotheses we derived form literature on the evolution of cognition. Yet we are very well aware of the limitations of this work. First of all, we concentrated on the evolution of personality characteristics that affect the cognitive processing of people instead of the evolution of cognitive processes themselves. Whereas the results appear interesting and promising to us, we are convinced that we should strive towards more theoretical backup behind the line of reasoning. Two ways appear to be possible. First of all we should widen our survey regarding scientific literature on the field of cognitive processing, evolution, personality and environment. Second we should try to find empirical data regarding the distribution of personality characters (Big Five, Hofstede's dimensions of culture) in countries having a different history in managing their (scarce or abundant) resources.

Second, we intend to experiment with the evolution of cognitive processing instead of the personality factors. This evolution may focus on the energy that is required for processing, as well as on the processing capacity itself. As regards the energy required for cognitive processing we should start with making a distinction between the energy required for deliberation and social comparison, as the latter clearly seems a smart (energy saving) strategy to profit (as a society) from the deliberation of one person. Also imitation would require more cognitive effort that simple repetition. Regarding the processing capacity itself we intend to formalise the size of the environment (distance of neighbouring cells) while deliberating/social comparing as a heritable factor. The more cognitive capacity, the larger the environment that can be taken into consideration. This implicitly incorporates a larger time-perspective in the agents, as the perception of more distant areas involves taking decisions on more future actions, as it takes more time to move to more distant areas. Also the number and similarity of other agents involved in the comparison/imitation process may be formalised as a heritable factor as to experiment with the evolution of normative systems. In this line of modelling it would be worthwhile to focus on the emergence of institutions.

This first series of experiments we presented here is serving a research line that has two objectives. First, we intend to improve the realism of the cognitive processing of our agents whilst securing the simplicity of their architecture and the transparency of the results. Second we aim at contributing to the discussion on the evolution of cognition, personality characteristics and the role the environment plays. Whereas this issue may be most relevant for psychologists, also from the perspective of anthropology and demographics this model may be of use in developing hypotheses on the mediating effect of cognitive evolution in the relation between population size and the environment.

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