The Energetic Dimension of Emotions: An Evolution-Based Computer Simulation with General Implications

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Abstract

Viewed from an evolutionary standpoint, emotions can be understood as situation-specific patterns of energy consumption related to behaviors that have been selected by evolution for their survival value, such as environmental exploration, flight or fight, and socialization. In the present article, the energy linked with emotions is investigated by a strictly energy-based simulation of the evolution of simple autonomous agents provided with random cognitive and motor capacities and operating among food and predators. Emotions are translated into evolving patterns of energy consumption related to situation-specific behaviors. As a result, a variety of behaviors resembling emotions ("fear" of predators, attraction to food, competition and/or collaboration with other agents, and so on) emerge, each with a specific pattern of energy consumption. There is little difference between emotion-like behaviors on individual and collective levels. The fact that these patterns evolve under a strictly energetic selection regime indicates the interesting role and adaptive advantage of emotions as situation-specific energy savers. Although gained through an approach characterized by a highly reduced complexity, these findings support a quantitative understanding of emotions that may improve the existing qualitative approaches and could have far-reaching implications for further research on and conceptualization of emotions and their interactions with cognition.

Keywords

affect logic, affects, cognition, emotion, emotion-cognition interactions, energy, evolution, simulation

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The aim of this study is to show, by a computer simulation going back to the possible origins of emotions, that the link between emotions and energy consumption is probably one of their most essential properties. It has long been generally understood that emotions have deep evolutionary roots (Darwin 1872; Panksepp 1998; Lane and Nadel 2000), and also well established that basic emotions like fear, anger, pleasure, and sadness are characterized by specific sympathicotonic or parasympathicotonic patterns of energy consumption associated with behaviors like flight or fight, food intake, socialization, and sexuality (Selye 1946). Each emotion may, in fact, be characterized by a specific profile of local and global energy consumption. On the phenomenological level, too, the energy-related effects of emotions on cognition and behavior are obvious both in animals and humans; although mostly stimulating, they can sometimes (as in freezing or depression) be blocking or inhibiting. Energy optimization within energetic selection regimes has long been a pivotal notion in evolutionary science (Lotka 2005; Wagner 2005). Different emotions can therefore be understood as situation-specific, goal-directed patterns of energy dissipation related to specific motor and sensory behaviors selected by evolution for their survival value.

Perhaps because notions such as "mental energy" and "emotional energy" are often used metaphorically and unscientifically, the relation between energy and emotion has largely been neglected by science. Indeed, energy—in the objective sense of measurable bioenergy, regularly ingested as food and differentially consumed through situation-dependent action by all living organisms—plays virtually no role in either the predominant general concepts pertaining to emotions (LeDoux 1996; Panksepp 1998; Forgas 2000; Lane and Nadel 2000; Damasio 2003; Davidson et al. 2003; Ketelaar 2004; Nesse 2005), or in studies focused on specific emotions such as jealousy, sexual desire, shame, and depression (Watson and Andrews 2001; Harris 2004; Nettle 2004).

Yet the energy dimension of emotions has not been neglected in all fields. Explicitly or implicitly, it has been considered important in early psychoanalysis and modern neuropsychoanalysis (Kaplan-Solms and Solms 2002), in certain sociological approaches (Collins 1993; Summer-Effler 2002; Turner 2007), in some empirical studies on robotics (Inoue and Kobayashi 1997; Gadanho and Hallam 2001; Yu and Xu 2004; Kato and Arita 2005), and also in the comprehensive theory of emotion–cognition interactions called affect logic, the inspiration of the present study (see below). Recent experimental studies on mating preferences carried out by Li and Kenrick (2005) and based on the attribution of a cash value (a symbolic equivalent of energy) to preferred personality traits are also implicitly energy oriented. Empirical research on the energy linked to emotions is, however, still in its infancy and to our knowledge, nobody has as yet explored the possible roots of emotions in fundamental evolutionary energy economics, our intention here.

An explicit focus on the energy aspects of emotions might, in fact, have significant advantages, with the added benefit of interesting general implications. Since energy consumption by the brain and the body is precisely measurable in different emotional states, both empirical research on and theoretical conceptualization of emotions could be put on a more secure basis by including this dimension, thereby complementing the current mainly qualitative and descriptive approaches, which are based on such factors as facial expression, vocal and motor behavior, neurovegetative functions, and subjective experience. An energy-based approach might also shed light on the crucial and still unsolved problem of how to achieve a generally accepted definition of emotion (cf. Kleinginna and Kleinginna 1981; Damasio 2000; Ciompi and Panksepp 2005). For example, specific energetic profiles could be established for the different so-called basic emotions (interest/curiosity, fear, anger, pleasure/joy, sadness, and so on; Ekman 1992; Izard 1992) and for a number of overlapping phenomena variously labeled feelings, emotions, affects, and moods, depending on the author and discipline involved. Another problem, the difficulty of obtaining a clear, agreed distinction between emotion and cognition, continues to hamper research on emotion–cognition interactions (e.g., through contrary views on the cognitive or emotional nature of appraisal; cf. Lazarus 1999; Zajonc 2000) but might be resolved in part if emotions are understood as phenomena based essentially on energy dissipation and differing fundamentally from the perception-based phenomena of cognition.

All this led us to the idea of exploring the relations between emotions and energy through a computer simulation of the evolution of agents provided with elementary sensory-motor capacities. Initially moving at random between energy sources ("food") and predators, the agents are eventually submitted to a classical evolutionary selection regime based on energy economics. If minimizing energy loss were enough, in such an experiment, to produce behaviors that resemble emotions in agents that resemble simple living organisms, then the hypothesis of an energy-based origin and nature of emotions would become quite strong. The hypothesis would be further reinforced if each specific kind of "emotional" behavior were accompanied by a particular pattern of energy consumption. And if "emotional" patterns similar to those on the individual level were also to appear at more complex levels of collective group behavior, then one might infer that similar basic energy dynamics underlie emotions at both elementary and more advanced stages of evolution, including higher animals and probably humans. This would also support the so-called fractal hypothesis of emotion–cognition interactions, which postulates that affective–cognitive dynamics may have basic similarities on different individual and collective levels, especially concerning the below-specified modulating, so-called operator effects of emotions on attention, perception, memory functions, and behavior that are similarly observed in individuals, smaller and larger groups, and even at the level of whole nations (Ciompi 1997; Ciompi and Baatz 2005).

Unlike most of the cited studies that include an energy dimension, our research starts at the most basic evolutionary level possible so as to first clarify the question of the energy-related origin and nature of emotions before moving on to more complex issues. For the same reason, our research is based exclusively on energy economics, in order to avoid contamination by additional problems, for example those related to the development of specific behaviors before the situations to which they may pertain appear, or to the dynamics of learning and memorization in artificial neural networks.

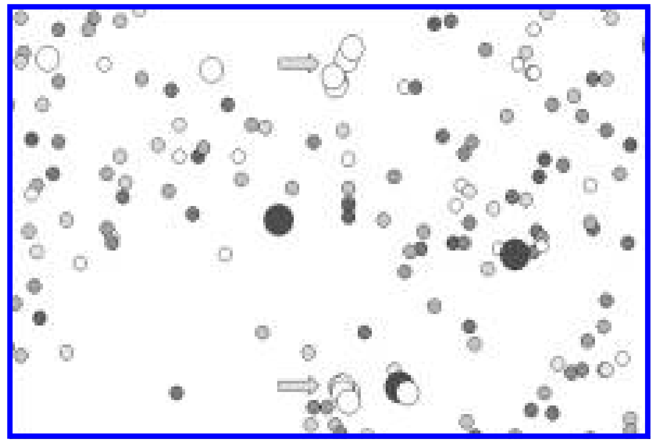

Figure 1.
Action field. Autonomous agents (big white circles) operate among randomly moving predators (big black circles) and randomly distributed food with low or high energy content (small clearer or darker gray circles). High-energy food can only be eaten by collaborating groups (arrows).

Conceptual Guidelines and Methods

Basic Concepts

The approach chosen is inspired by the theory of affect logic, which seeks to integrate the available psychological, sociological, and biological knowledge about emotions and emotion–cognition interactions under a general system-theoretical perspective (Ciompi 1988, 1997). In this theory, basic emotions or affects (the latter term is used here as an "umbrella notion" covering all kinds of overlapping emotion-like phenomena) correspond to goal-directed patterns of energy consumption that are linked through evolutionary selection to specific cognitions and motor behaviors. An important implication of this definition is that relaxation and indifference are also "affective states" with specific effects on cognitive and motor behavior. From the perspective of affect logic, then, completely "neutral" states do not exist: affective–cognitive interactions are omnipresent.

In parallel to the notion of a "bit" (the smallest perceivable difference according to information theory, cf. Shannon and Weaver 1949), cognition, on the other hand, is defined as the capacity to perceive and further process sensory differences. This equally broad but precise definition (which includes different cognitive capacities such as perception, attention, memory, and combinatory thought) clearly distinguishes cognition from emotion, thus facilitating the study of their circular interaction: cognitions trigger specific emotions that, in turn, exert selective, so-called operator effects on cognition and behavior, such as (1) shifting the focus of attention; (2) narrowing or widening perception; (3) stimulating or inhibiting certain motor activities; and (4) mobilizing or blocking specific memories and thoughts.

Another important postulate of affect logic and modern psychology is the thesis that the interactions between emotion and cognition are generally not linear (Schuster 1991; Ciompi 1999, Tschacher and Dauwalder 1999), presenting instead sudden so-called bifurcations when emotional tensions reach a critical level (e.g., in a sudden shift from love to hate, from fear to aggression, from normality to psychosis, or from a dominating "logic of peace" to a "logic of war"). The hypothesis that certain aspects of affective–cognitive interactions may have a fractal structure (i.e., that the above-mentioned operator effects of emotions on cognition and behavior are self-similar on different individual, microsocial, and macrosocial levels) is also of relevance to this study (Ciompi 1988, 1997, 1999; Ciompi and Baatz 2005).

An Evolution-Energetic Model of Simulation

The model consists of a population of energy-driven autonomous agents with elementary capacities for perception and movement, regulated by gene-like programs, and submitted to slow evolutionary change. The agents (big, clear-gray units in Figure 1) move around between "food" (small, gray units in Figure 1) they can "eat" when meeting them, and predators that hunt them (black units, Figure 1)

To start with, the agents perceive and move around at random distances apart and in random directions, independent of any perception of food, predators, other agents or even an absence of objects. This initially random behavior is submitted to an energy-based evolutionary selection regime. The result is that only individuals that accumulate enough food energy can survive to transmit their behavior to a next generation of agents, while unsuccessful individuals die out.

Emotion-like phenomena are operationalized as evolving patterns of energy consumption that emerge in relation to the various possible perceptions and movements (the so-called food mode, predator mode, and fellow-agent mode, according to the dominant object perceived, or an exploratory mode when no object is perceived). The absolute amount of energy consumed in relation to a given cognitive or motor behavior provides a quantitative measure of the "strength" of the related emotion-like phenomenon, while the relative amounts of energy consumed provide a quantitative base for comparing the evolution of different emotion-like phenomena under different environmental conditions (cf. Figures 2–6). Energy consumption grows in proportion to the freely evolving range of perception and the freely evolving range of movement toward or away from predators, food, and fellow agents. Additional types or objects of perception and of motor behavior cannot emerge spontaneously in this model, but they can be switched on and off as frame conditions of a simulation.

Each agent is initially given a fixed number of "energy units" that decreases with the square of each step of movement and/or perception, and increases when food is captured. The number and size of the food units—the crucial, freely defined initial conditions—are randomly distributed. Catching (meeting) food increases the agent's energy by the energy content of the food. Large (high-energy) food units (the small, dark gray units in Figure 1) can only be "eaten" through cooperative group action (agglomerated agents in Figure 1, see arrows). Agents that lose all their energy die. Meeting a predator at any point also leads to instant death.

Evolution is simulated through a predefined number of generations (life cycles), each with a predetermined lifespan (number of action steps). An agent surviving until the end of its lifespan multiplies into a number of genetically identical offspring proportional to the accumulated amount of energy it has obtained. The behaviors of the surviving agents are thus asexually transmitted from generation to generation, while unsuccessful behaviors are eliminated. Evolutionary change is implemented by small random mutations of the genetic program in each generation.

Methods

The genotype of each agent is modeled as a haploid set of 10 "genes," each of which is represented by a rational number submitted to evolutionary change: four gene loci (one for each perception mode: food mode, predator mode, fellow-agent mode, exploratory mode) code for speed (step size) and direction of movement (toward or away from the perceived object), and another four code for the range of perception. A value y in a gene coding for movement will result in a movement of y spatial units and a consumption of y^2 energy units. A value x in a gene coding for perception will result in a perception range of fx spatial units and a consumption of x^2 energy units, where f is a factor that scales perception range against step size. Two additional genes code for two evolving dominance coefficients (food/predator and food/fellow agents coefficient), which regulate the "dominant" (preferred) focus of perception that determines behavior when different objects are simultaneously perceived. Random mutations occur at a rate of 10^{-2} (0.01) per generation, according to a normal probability distribution times 0.5. Predators move toward the nearest agent. Each agent's behavior is determined by its nearest dominant focus of perception.

To capture food, some "food-eating energy" is used to overcome "food resistance," the amount of "energy" involved increasing with the size of the food parcel. Large-size food can therefore only be eaten through the collaboration of groups of agents. A collaborating group is defined as a cluster of agents with coordinated action in spatial proximity (<10 pixels) over at least 15 action steps.

The frame conditions that define the experimental scenario—field dimensions, initial population of agents and predators, size and quantity of food units per generation, and so on—can be varied arbitrarily. By trial and error, the following "standard" conditions were found to favor long-term evolution: action space = 1000 pixels; initial agent population = 2500; initial energy load per agent = 100; number of predators = 15; action steps per generation = 400; number of generations = 2000; food units per generation = 15; food energy = 100; food resistance = 8% of food size (energy load); food-eating energy = 10.

About 50 parameters of interest (including population size, number of individuals dying, direction and speed of movement, range and dominant focus of perception, patterns of energy intake and consumption, and group formation and size) were continually monitored. The simulation program is written in Visual C++. It runs on Windows systems and is available at http://www.affect-logic.com/3.html.

Hypotheses

Our assumptions lead us to the following operational hypotheses:

(1) In each functional mode (food mode, predator mode, fellow-agent mode, exploratory mode) perception-specific patterns of motor and cognitive behavior emerge and stabilize through evolution. They are characterized by different directions and speeds of movement, and different ranges and dominant focuses of perception.
(2) Each mode is also characterized by a specific pattern of energy dissipation, that is, emotion-like phenomenon, in the sense of our definition.
(3) Such "emotions" show similar patterns of energy distribution in individuals and groups of different sizes.

These three hypotheses were systematically tested by 10 simulation runs over 2000 generations in each mode of function under standard conditions, both at the individual level and at the level of smaller and larger groups. In addition, a number of relationships between environment and evolution

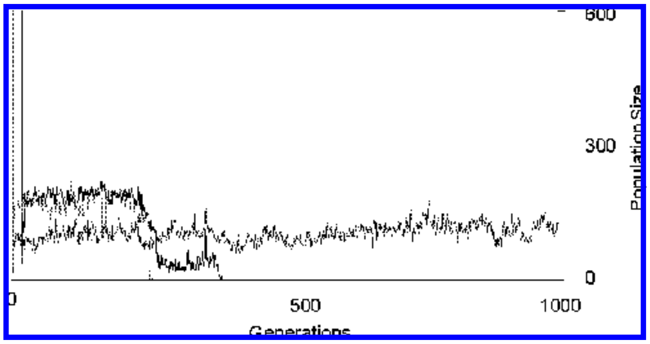

Figure 2.
Evolution of agent populations under favorable and unfavorable conditions. Long-term survival (medium dark gray line) occurs when quantity of food, number of predators and field dimensions are well balanced. Populations die out when predators are too abundant (clear gray) or food is insufficient (black).

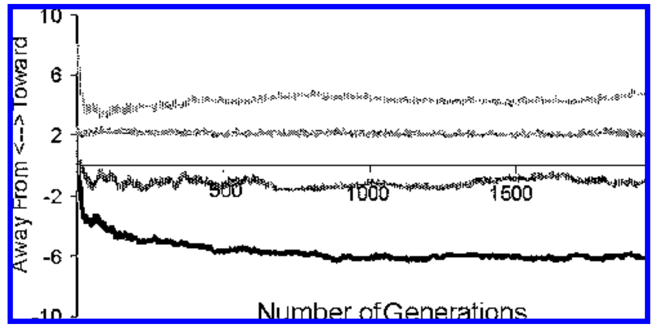

Figure 3.
Evolution of energy investments for motor behavior in different functional modes. Highest absolute amounts of energy are invested for flying away from predators (predator mode, bottom black line; end value $y = -6.07$), followed by exploratory mode (top clear gray; $y = 4.72$), food mode (medium gray; $y = 2.13$), and fellow-agent mode (dark gray line; $y = -1.21$) (y = average energy consumption in 10 simulation runs. $Y > 1$ = moving toward; $y < 1$ = moving away).

were selectively studied, and some nonlinear and other atypical evolutionary dynamics were looked at under nonstandard conditions.

Results

A first general result is the fact that a large number of context-dependent evolutionary processes can be realistically modeled by this approach. Specific patterns of coevolving cognitive and motor behavior, characterized by specific patterns of energy consumption ("emotions," in the defined sense), emerge in all four functional modes, as predicted by hypotheses 1 and 2. The population dynamics are entirely determined by the energy balance resulting from complex interactions between genetically steered behaviors and the environment. Under unfavorable conditions (e.g., insufficient food, too many predators, too small an initial population, too low the initial energy per agent) populations die out rapidly (Figure 2).

Under standard conditions, evolution continues over thousands of generations, typically showing the following three phases: during the first 2–3 generations, a drastic reduction of the high initial random genetic variability occurs through evolutionary selection, with survivors who happen to have a behavior that is appropriate to the situation accounting for only 5–10% of the original 2500 agents under standard conditions. The next phase is characterized by minor fluctuations of population size and behavior over several hundred generations, related to progressive energy optimization. Finally, most parameters tend to stabilize on attractor-like levels of optimal energy dissipation, or emotion-like phenomena, as long as frame conditions are kept constant.

In terms of motor behavior (direction and speed of movement), the following mode-specific patterns gradually emerge (Figure 3). Motor behavior triggered by the perception of a predator (predator mode) is increasingly characterized by high-energy consumption for quick flight. Much energy is also used for quick exploratory movements when no object is in

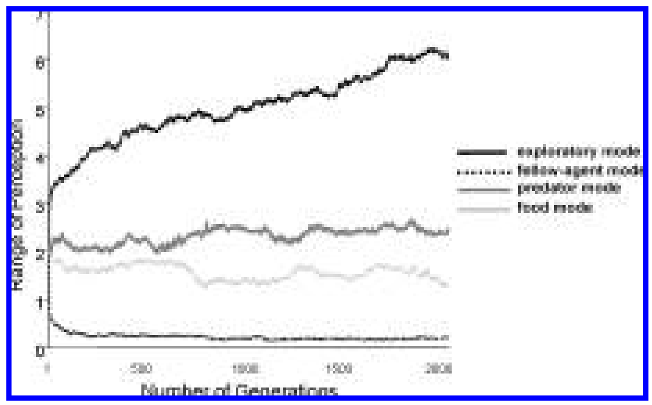

Figure 4.
Evolution of energy investment for cognitive behavior in different modes of function. Most energy is invested for expanding the range of perception in the exploratory mode (top black line; end value $y = 6.09$), followed by predator mode (dark gray; $y = 2.40$), food mode (clear gray; $y = 1.31$), and fellow-agent mode (black; $y = -0.21$) (y = average energy consumption in 10 simulation runs).

sight (exploratory mode). Moving toward food (food mode) gets third priority, only minimal energies being invested in slowly moving away from detected fellow agents (fellow-agent mode). These patterns resemble increasing "fear" of predators, intense "interest" or "stimulus-hunger" when no object is perceived, and moderate attraction to food ("pleasure") as long as food remains relatively abundant (standard conditions). Avoiding ("disliking") fellow agents represents a form of competition, because it increases each agent's chances of meeting food.

The emerging cognitive (perceptive) behavior, too, is mode specific (Figure 4). Most energy is used in the exploratory mode, mainly to expand the range of perception when no object is perceived. A lot of energy is also invested in increasing the range of object recognition in the predator and food modes, but when the only things perceived are other agents (fellow-agent mode), the energy consumption allotted

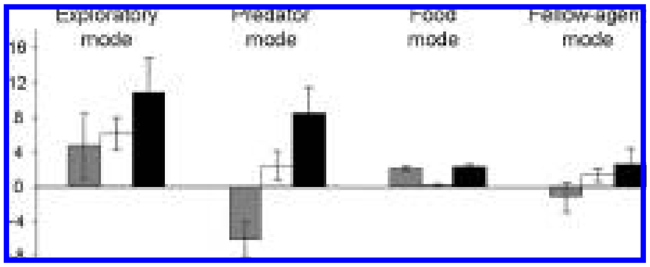

Figure 5.
Different patterns of energy consumption in different modes of function (explanation in the text). Gray = energy spent for moving toward ($y > 1$) or away ($y < 1$) of the perceived object. White = energy spent for object perception. Black = absolute amount of energy spent both for movement and perception (y = average end-values of energy consumption in 10 simulation runs over 2000 generations).

to object recognition is minimized by reducing the range of perception.

The same hierarchy of energy consumption is mirrored by the evolution of the behavior-relevant focus of attention, regulated by the two above-mentioned dominance coefficients, when different objects are simultaneously perceived. Predator perception becomes increasingly dominant over food perception, which, in turn, dominates fellow-agent perception.

Each perception-triggered mode of function is therefore characterized by a specific pattern of energy dissipation, that is, "emotion" in the defined sense (Figure 5). Particularly high amounts of total energy consumption ($y = 10.8$, black) develop in the exploratory mode, mainly to expand ("speed") the range of movement (gray) and to widen the range of perception (white). In the predator mode, too, the total energy consumption is high ($y = 8.5$), again mainly for a fast escape, but also to expand the range of perception. Energy consumption decreases dramatically, by contrast, in the food and fellow-agent modes ($y = 2.3$ and 2.5, respectively) where movements are maximally slowed down and perception is narrowed. Again, these patterns resemble "emotions" in the sense of hypothesis 2: the highest "emotional arousal" corresponds to high "interest/curiosity/stimulus hunger" when no object is in sight, or to intense "fear" when a predator is perceived, and both states contrast strikingly with the relative "relaxation" and/or "indifference" demonstrated when only food or other agents are in sight.

All such patterns depend, however, on the frame scenarios, especially on the number and size of food and predators. When food becomes less abundant than under "standard" conditions and competition between agents therefore gets tougher, early perception of competing agents becomes progressively more important and finally dominates over food perception. When food units get so large that they can only be taken in ("eaten") by collaborating agents, mutual avoidance between agents turns into mutual attraction, in order to form collaborating groups (or, rather, swarms) of roughly 3–50 individuals, depending on food size. Mutual avoidance ("dislike") tends, however, to reappear (with some instability, or "ambivalence," cf. Figure 6, column 5) between competing groups. Essentially similar, emotion-like behaviors thus emerge at different levels of evolutionary complexity, as predicted by hypothesis 3.

Exploratory simulations beyond standard conditions reveal additional "emotions," which exhibit atypical and nonlinear dynamics that have not been fully studied. Random genetic drift (Lande 1976) obviously plays a significant role, since populations regularly go through intermediate periods of small population size. Surprisingly, when a few local predators eliminate competing agents so radically that local food accumulation outweighs predator damage, agents may tend to be "attracted" to rather than "fear" predators. Sensitivity to initial conditions is seen when unusual initial constellations lead to atypical, long-term evolution. Sudden bifurcations occur, for example, when apparently robust populations abruptly die out or when frame conditions change radically. Behavior toward predators that exert no significant evolutionary pressure because they are few or weak may show free-running (chaos-like) dynamics resembling "ambivalent" oscillations between "fear," "attraction," and "indifference."

It is, furthermore, striking that the exploratory implementation of new cognitive capacities leads almost regularly to the emergence of new emotion-like phenomena. For instance, agents provided with the ability to compare their own strength (their energy load) with the strength of a predator develop a program through the evolutionary process that makes them run away from ("fear") only strong predators while ignoring weak ones. If agents become able to assess their own strength against that of other agents, a kind of "emotional contagion" (imitation of stronger individuals, cf. Hatfield et al. 1994) appears, contributing to group stabilization. Implementing the new capacity to distinguish between agents belonging to their own group and "strangers" also strengthens a behavior that resembles bonding with group members. Overtly aggressive behavior beyond mere competition appears if agents are given the ability to damage (reduce the energy consumption of) or kill other agents and/or predators.

Discussion

The reported data show, in summary, that a strictly energy-based simulation of the behavioral evolution of comparatively very simple agents yields a surprisingly rich variety of basic "emotions" in the defined sense, such as "fear," "attraction," "dislike," "competition," and "indifference." In addition, different forms of sensorimotor behavior emerge in different modes of emotional functioning, reproducing three out of the four operator effects of emotions on cognition and motor functions postulated above (1–3; 4 has not been tested). Their similarity at both individual and various group levels corresponds

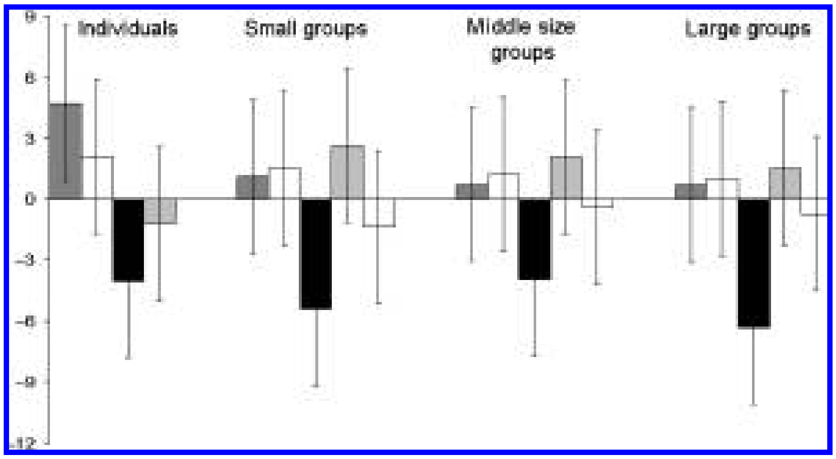

Figure 6.
Comparison of emotion-like behaviors of individuals and groups. Similar patterns of emotion-like behavior emerge on the individual and on various group levels. Most energy is generally spent for fear-like flight from predators (negative values of the third columns, black). "Interest" for environment exploration (first columns, dark gray) and "attraction" toward food (second columns, white) depend on context. Mutual avoidance ("dislike") between individuals turns into attraction when increasing food size induces collaboration (initial negative and then positive values of forth column, clear gray), but reappears between groups (negative value of fifth columns, white) with, however, some "ambivalence," as shown by the standard deviation.

to the expected fractal structure of the modulating influence of emotions (what we call "operator effects") on cognition. Additional "emotions" emerge under special conditions, especially when new cognitive capacities are implemented. These findings support both our basic hypotheses of emotions: that their origin can be found in energy considerations, and that they have modulating effects on cognitive and motor behavior.

It appears a specific strength of the chosen approach that these patterns evolve freely and repeatedly in different simulation runs with similar frame conditions but different random initialization of the first generation of agents. The fact that the emergence of new emotions goes hand in hand with the appearance of new cognitive and behavioral capabilities suggests that the main evolutionary driving power behind the development of emotions is their adaptative advantage. To our knowledge, these observations are new in the field of simulation of emotions. Their appearance even at the very elementary levels explored so far suggests that situation-specific energy dissipation is, indeed, a fundamental property of emotions.

The emotion-like nature of the observed phenomena may, however, be questioned. Computer simulations obviously replicate nothing of the unique subjective qualities of human emotions, nor do the simple frame conditions we have implemented replicate the complexities of a natural environment. But human emotions might essentially consist, as proposed by James and Lange over a hundred years ago and recently reemphasized (James and Lange 1885; Damasio 1994), of the conscious perception of global somatoenergetic states. That emotion-like behaviors emerge on such a narrow basis is all the more remarkable. Nesse (2005), too, emphasizes in point 4 of his interesting "Twelve crucial points about emotions, evolution and mental disorders" that elementary emotion-like phenomena may emerge even at the level of unicellular organisms. There is probably a deep, functional continuity of emotion-like phenomena occurring at all levels from less to more highly differentiated animals and even to humans, at least concerning the explored energy dynamics and the postulated situation-specific operator effects of specific emotions on cognition and behavior. Phenomenologically, the patterns that emerge correspond so closely to such well-known basic emotions as fear of (running away from) predators, pleasant attraction to (approaching) food, and the ambivalent competition or collaboration between agents generally observed in similar situations at higher evolutionary levels, that in our view their emotion-like character may safely be postulated.

A further objection is that rather than "emotions," the emerging patterns of energy consumption reproduce mere sensorimotor behaviors. Again, however, their striking resemblance to behaviors typically labeled as emotional at higher levels supports the assumption that the observed patterns actually do correspond to the evolutionary roots of emotions.

Another possible objection may be that simulations can never substitute for real observations, and that the frame conditions of a simulation may be manipulated in order to obtain the expected results. But, how *can* one investigate early evolutionary stages if not through simulation? And choosing frame conditions that favor evolution (like the "standard conditions" we have developed through trial and error) is nothing but an imitation of the fact that in nature, too, successful evolution preferentially takes place in a favorable environmental niche. Moreover, the possibilities of manipulation are severely restricted by the choice of a very basic and exclusively energy-centered simulation model.

We therefore believe that the described simulations reproduce quite realistically fundamental aspects of the evolution of energy economics in living organisms, all of which are, in essence, open, energy-processing systems provided with cognitive and motor capacities. If this interpretation is correct, context-dependent energy dissipation is a core dimension of emotion-like phenomena in all organisms. The reported multilevel similarities point in the same direction. It should also be noted that the simulated abstract "agents," "food units," and "predators" are, in principle, dimensionless, that is, scale independent. They may hence represent both very simple and very complex biological and social entities.

Emotions appear in this light as crucial energizers and modulators of all individual and/or collective behavior (Collins 1993; Ciompi 1997; Turner 2007). If further confirmed, this quantifiable approach, which usefully complements the conventional qualitative–descriptive definitions of emotions, may be of general interest far beyond its value as mere simulation. As briefly mentioned above, it may offer a variety of advantages for the study of emotions and their interactions with cognition:

1. Taking into account the energy dimension of emotions allows us to differentiate them more clearly from cognition and, therefore, to study emotion-cognition interactions on a more secure basis than before. In addition, the energy approach provides a plausible explanation of the omnipresent interaction between these two fundamental aspects of mental functioning (cognition providing structure and emotion providing dynamics), thus helping to clarify a particularly crucial issue in this domain. Moreover, the observed relation between the arbitrary implementation of new cognitive capacities and the emergence of more differentiated emotion-like phenomena suggests that on higher evolutionary levels, too, cognitive differentiation may be a necessary precondition for further emotional differentiation.

2. As energy flows in both brain and body are now easily measurable, thanks to modern imaging techniques, the proposed approach may lead to new opportunities for quantitative research in a field still hampered by a multitude of mostly qualitative and partly contradictory definitions. Both the energy profiles of the overlapping phenomena variously called affects, emotions, feelings, moods, and motivations, and their interactions with attention, memory, and comprehensive thought could thus be more precisely defined and studied. The postulated specific energy profiles of different emotions, too, could be quantitatively investigated.

3. Exploration of the biological, psychological, and social effects of emotions under one leading principle—namely, energy dissipation—is highly economical, conceptually. It may facilitate interdisciplinary communication and the transfer of knowledge from one field of research on emotions to another, especially if the hypothesis of a fractal structure of certain emotion–cognition interactions is confirmed.

4. The systematic linking of cognition (in the defined perception-related sense) to emotions (understood as goal-directed patterns of energy consumption related to specific situations) is both a necessary and a sufficient condition for creating a survival-relevant "world model" of any degree of complexity (Ciompi 1997), whereas both cognition and emotion alone are insufficient. Integrating the energy dimension into our concept of emotions may therefore lead to a new understanding of the dynamics of mental functioning in general, and also of the necessary components of "intelligent machines" in robotics, a domain where emotion–cognition interactions are becoming a central focus of interest (Sloman 1999; Binnig et al. 2002; Scheutz 2004).

5. According to generally accepted system-theoretical concepts, nonlinear bifurcations in the global functioning of open, dynamic systems are provoked by critical increases in energetic tensions (Prigogine and Stengers 1983; Haken 1990). Taking into account the energetic dimension of emotions may therefore also lead to new insights in the crucial role played by such tensions in sudden global shifts in the dominating patterns of thought and behavior that often occur in mental and/or social systems (Ciompi 1997, 1999; Ciompi and Baatz 2005).

Obviously, the numerous implications of this new focus can lead to new research questions. For example, what is the specific energy profile, at both local (e.g., cerebral or peripheral) and global (e.g., organismic) levels, of specific emotions and of related phenomena such as moods, motivations, and drives? What are the precise interactions of particular emotions with specific perceptions, thoughts, and memories? How can the local and global levels of emotional tension be measured in different mental or social systems, and what are the nonlinear effects of increasing emotional tension in individuals and in collectivities, whatever their size? Questions such as these are of considerable theoretical and practical interest in several fields of science and technology, from biology, psychology, and sociology to AI and robotics. In conclusion, therefore, we believe that the proposed approach focused on energy is promising, and suggest that it be replicated and explored further, both in general research into emotion and emotion–cognition interactions and in more sophisticated simulations.

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