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RESEARCH REPORT

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Using artificial life to teach evolutionary biology

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Abstract This paper presents a pilot study on the use of artificial life software in an educational setting. Two groups of high school students received a standard lesson in evolutionary biology followed by a software session. The experimental group used the suite of artificial life software presented in this paper; the control group used a commercial multimedia hypertext. At the end of the software session both groups were asked to fill in a simple multiple-choice questionnaire testing the students' knowledge of various aspects of evolutionary biology. The results show that the group using the artificial life software performed significantly better than the control group. We argue that the experimental group may learn more effectively because the artificial life makes it possible for students to perform experiments, a possibility not available to the control group.

Keywords Artificial life · E-learning · Evolutionary biology

Introduction

The Darwinian theory of biological evolution is a well-established scientific theory describing fundamental laws governing all biological organisms. For most schools the successful elucidation of the core of this theory is a key educational goal. Teaching evolutionary biology to young people can strongly influence perceptions of the validity of scientific method and evidence. This is especially true in the USA where, in 1999, for instance, the Kansas State Board of Education removed evolutionary biology from the high school curriculum and deleted Darwinian theory from state assessments of student performance. The National Academy of Science (1998) is currently stressing the importance of evolutionary biology and is funding specific teaching/research programs in this area.

In the 60's, Piaget (1967, 1970) demonstrated that hands-on experimentation is the basis for cognitive development. This suggests that evolutionary theory could also be taught in this way. Unfortunately, the evolution of species requires time and it is impossible replicate in a standard didactic laboratory this kind of phenomena. As a consequence evolution is taught "verbally", in a classroom setting, and only rarely in the laboratory. As a partial solution to this difficulty, multimedia products have been proposed, which use attractive images, sound and animation to explain the fundamental concepts of evolution (Montateti 1998). Although these products are a significant step forward, they do not allow the students to experiment or to make direct observations. The learner watches, listens and reads but has no opportunity to intervene in the processes being observed.

It has been argued (Towne et al. 1994; Towne 1995; Pappo 1998) that computer simulations can be used as a powerful teaching tool, allowing the learner to manipulate key variables and to observe the consequences, while avoiding over-reliance on purely verbal channels of communication. Using simulation, the user becomes a researcher, working in a virtual lab. Over the last 10 years, basic research in artificial life has produced algorithms, software and hardware, which imitate biological mechanisms and processes, allowing their simulation on a vastly compressed time scale. On the web, it

The website for Cognitive Technology Lab is http://ctlab.unina2.it; for Laboratory of Artificial Life and Robotics http://gral.ip.rm.cnr.it/; and for Maersk Mc-Kinney Moller Institute for Production Technology http://www.adaptronics.dk.

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is possible to find many types of software that allow a user to play with artificial life creatures (for a good starting point see website: http://zooland.alife.org/). Typically, however, these models focus on entertainment or on showing the potential of artificial life as a new technique in computer science. The BBC education site takes a different approach. The site contains traditional materials on evolution (see http://www.bbc.co.uk/education/darwin/alife/), such as the on-line version of *The Origin of the Species*, and a nice artificial life simulation called Biotopia (see http://www.bbc.co.uk/education/darwin/). Using Biotopia, a user can evolve artificial life creatures that struggle for survival. Biotopia has a user community that describes, discusses and compares artificial organisms evolved by users. From a biology teaching perspective Biotopia provides little to no help in the teaching of basic biological concepts. The software appears to be on the site mainly because it presents a vague analogy with various, not very well defined, biological phenomena. Many artificial life software packages offer complex micro-worlds where a user can manipulate many levels of an evolutionary process (e.g. environment, genotype, morphology, behavior) in such a way that the behaviors that emerge from the simulation cannot be attributed to the action of any one specific variable. If used for recreational purposes these micro-worlds can be fascinating. From an educational perspective, however, they are far too complex to communicate scientific concepts clearly.

This is a key issue in the design of artificial life tools that are going to be used for educational purposes. For this reason, the suite of artificial life software described in this paper allows the user to manipulate just one or two variables at a time.

Despite these weaknesses the authors strongly believe that well-designed web-based artificial life software like Biotopia, in which one variable is manipulated at a time, can play a crucial role in supporting standard classroom lessons in basic biological theory. We can design artificial life software as a virtual laboratory in evolutionary biology where students can reproduce phenomena described in their textbooks. In short, the gap between teaching experimental natural science and evolutionary biology can be bridged by well thought out experiments in artificial life.

Working together with biology teachers we designed a lesson supported by artificial life software originally produced for research. The lesson concentrated on the concepts of creationism vs. evolutionism, Lamarckian vs. Darwinian evolution, selection mechanisms, artificial vs. natural selection and the role of the environment in genotype–phenotype mappings. The teaching strategy was based on an incremental approach, in which different software tools were used to demonstrate different aspect of evolutionary processes: In particular:

1. the role of artificial selection and mutation operators was illustrated using a program in which users evolved the facial expressions of artificial agents;
2. the role of the environment and individual learning in genotype–phenotype mapping was introduced using a simulator to evolve/train simulated LEGO robots;
3. the mechanisms of natural selection were investigated using an artificial life simulator of a population of artificial organisms, competing to win pieces of food.

In order to obtain an initial measure of the effectiveness of our approach we compared the performance of two groups of learners. In the first (experimental) group, users interacted with artificial life tools; in the second (control) group they used traditional multimedia hypertext. This comparative study shows that while the artificial life software and the hypertext tools both produced a statistically significant improvement in learning performances (i.e. higher scores on the questionnaire) the students who used the artificial life software achieved better learning performance.

Materials and methods

Experimental and control groups

Two groups, each consisting of 22 Italian high school students 14 to 15 years old, participated in a standard lesson on evolutionary biology given by their teacher. After the lesson, the experimental group used a suite of artificial life software while a control group used a traditional multimedia hypertext. In order to quantify the performance of the two groups we asked the students to fill in multiple-choice questionnaires. Questionnaires were administered before and after the lesson, and after the software session.

The questionnaire

The questionnaire, developed together with biology teachers, was designed to measure students' comprehension of basic concepts in evolutionary biology. It contained 14 questions, each of which was associated with four possible answers, of which only one was correct (see Appendix). The decision to use an extremely simple tool taking up little of the students' time was a deliberate one, taken in order to avoid psychological stress due to memory and attention overload.

The lesson

The lesson was a standard unit from a high school biology course and lasted 1.5 h. The teacher began by illustrating non-scientific theories about the origin of life (creationism and fixism). She then presented Lamarckian and Darwinian evolutionary theories. In this general framework, students were introduced to the concept of genotype, phenotype, selection mechanisms, and the role of the environment in genotype–phenotype mappings.

The hypertext

As a hypertext we used a commercial product published in Italy (Montateti 1998) and widely distributed in schools. The hypertext uses detailed text description, maps, pictures and animation to describe basic concepts in Darwinian evolution. The treatment is divided into several sections. Some of these explain the historical background and the socio-cultural context in which Darwinian thought developed; the others describe the Darwinian vision of the origin of species and of human beings. The product contains seven sections:

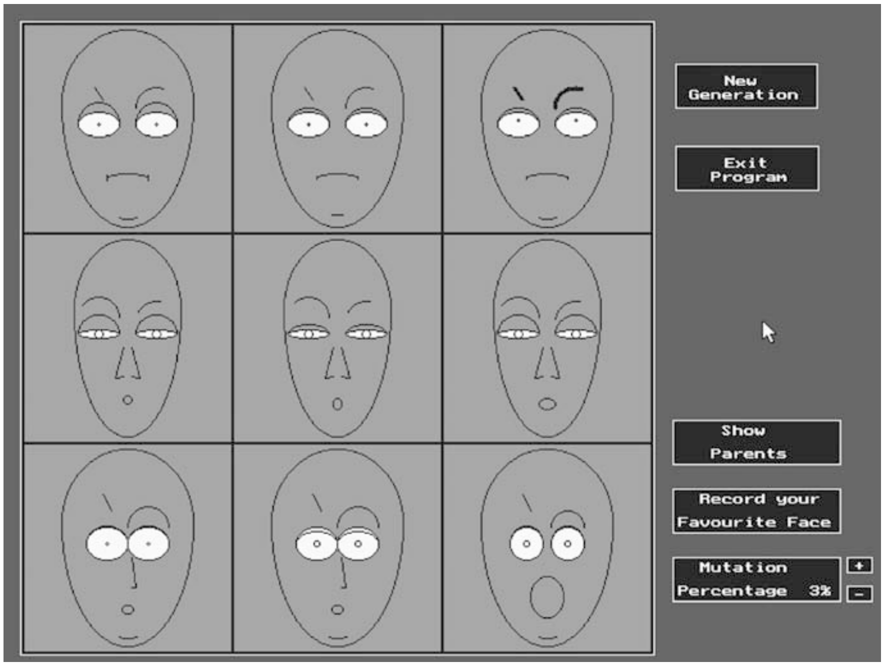

Fig. 1 How the game appears to the user of Face-It. Technically, we have a user-guided genetic algorithm that pilots the evolution of facial expressions. The user, after viewing the nine faces on the screen, chooses the three liked most. These will be the parents for the next generation of faces. Users can adjust the rate of mutation applied during reproduction

1. "Darwin's Life". In this section the hypertext shows a map of Great Britain where several active links allow the user to discover the most important places, facts and dates in Charles Darwin's life.
2. "Characters". The hypertext shows texts and photos of a large number of people, who played an important role in Darwin's life.
3. "Evolutionism". The hypertext reports anti-Darwinian theories of evolution (i.e. from Lamarck to the early 1900s).
4. "The Journey". A map full of texts and photos describing the famous journey of the 'Beagle' and reporting Darwin's observations along the way.
5. "The Beagle". A virtual tour inside the ship that Darwin used for his research.
6. "The Origin of Species". The hypertext presents the concepts of evolution and natural selection. These are explained with the help of texts, graphs and images. Darwinian and Lamarckian theories are compared.
7. "The Origin of Human Beings". In this section, animation is used to show a genealogy of modern human beings tracing their ancestry back to simple organisms.

Artificial life simulation tools[1]

FACE-IT The Face-It Project software package (Pagliarini, Parisi 1996; Pagliarini et al. 1996) uses a genetic algorithm to evolve pictures of stylized facial expressions. In the work reported in this paper, the package, which has been used in a number of different application areas (art and psychology, etc.), was used to teach the concepts of artificial selection, genotypes and mutation. Pictures are evolved on the basis of the user's evaluation of a number of facial expressions shown on the screen. The Face-It model was inspired by Leonardo da Vinci's facial studies, by artificial life techniques for user-guided evolution of images and by cognitive science studies of the recognition of facial expressions. In Face-It, a genetic algorithm is applied to a population of genotypes. Each individual's genotype is composed of a bit string coding 33 genes (continuous variables) that define 33 facial traits. The algorithm can produce approximately 400.000 different expressions. Face-It operates on a population of nine individuals. Each individual's genotype is initially random and maps to a face (the phenotype) that is rendered on the user's screen (see Fig. 1). Nine different genotypes code for nine different faces. It is important to note that, in this algorithm there is a one-to-one genotype–phenotype mapping. The user uses the mouse to select a subset of faces for reproduction. Each individual (i.e. expression) selected produces a fixed number of clones. Each clone is mutated in randomly chosen parts of the genotype (bit string). (Users can decide the average number of mutations per genotype). A new generation of faces then appears on the screen. The user can use a pop-up window to compare the expressions of parents and their offspring and see the phenotypic effects produced by mutation. This process of selection, cloning and mutation is continued until one or more satisfactory expressions are obtained.

TOYBOT ToyBot (Lund et al. 1997; Lund, Miglino 1998) is a tool that allows children to simulate interesting mobile robot behaviors. These can then be downloaded and experimented with on real robots. The original goal of the tool was to allow children to use hi-tech (i.e. robots) without applying "information processing methodology" (i.e. programming). In the work reported in this paper we concentrate on ToyBot's simulation capabilities. The model simulates the evolution of populations of artificial agents with elementary navigational abilities. Based on artificial life and evolutionary robotics techniques, the simulated environments allow the user to select for organisms with efficient sensory-motor behavior. In the work reported here we used the tool as a teaching aid, focusing students' attention on the role of the environment and individual learning in determining behavior (the phenotype). Robot behavior was "designed" by applying a user-guided genetic algorithm (UGGA, Fig. 2), and user-guided reinforcement learning (UGRL, Fig. 3) to the controller of the robot. Each controller consisted of a neural network (i.e. a model of the brain of the Toybot). During the application of the UGGA and the UGRL, robots' behaviors were displayed on the screen, allowing the user to judge their actions. In the UGGA a large number of ToyBots (and their behaviors) were presented simultaneously on the screen and the user had to select a subset

[1]The tools could be downloaded from software section of http://ctlab.unina2.it (Cognitive Technology Lab)

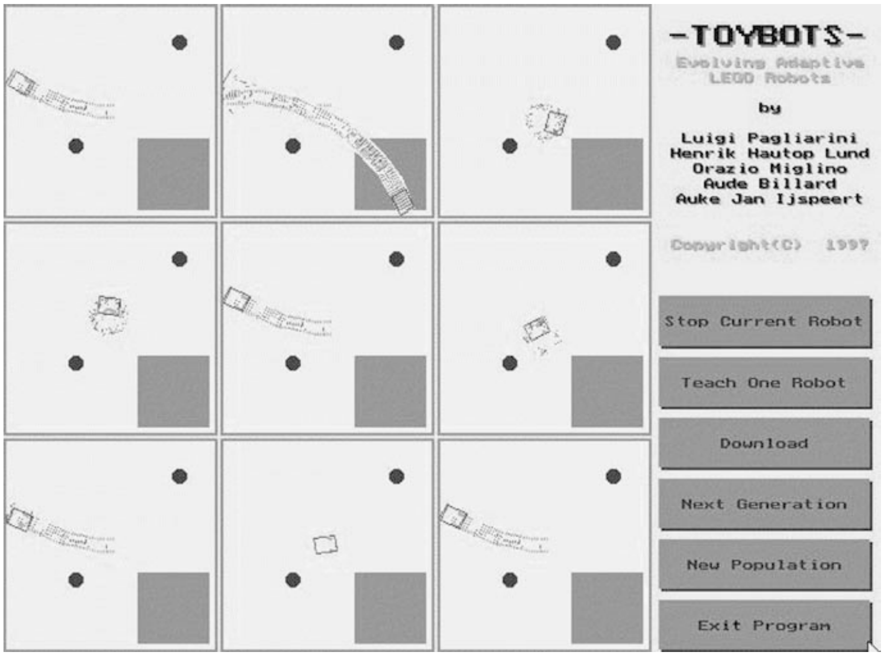

Fig. 2 One of the aspects of the ToyBot model: Darwinian evolution (of the behavior of artificial organisms). In this case, the technique used is a user-guided genetic algorithm. The user, after examining the behavior of nine different artificial organisms, uses the mouse to choose three organisms which will then be allowed to reproduce. The selected organisms generate a new population that will replace the existing one. In the long run, this mechanism is likely to produce organisms whose behaviors satisfy the user's expectations, thus demonstrating to the user the validity of Darwinian theory

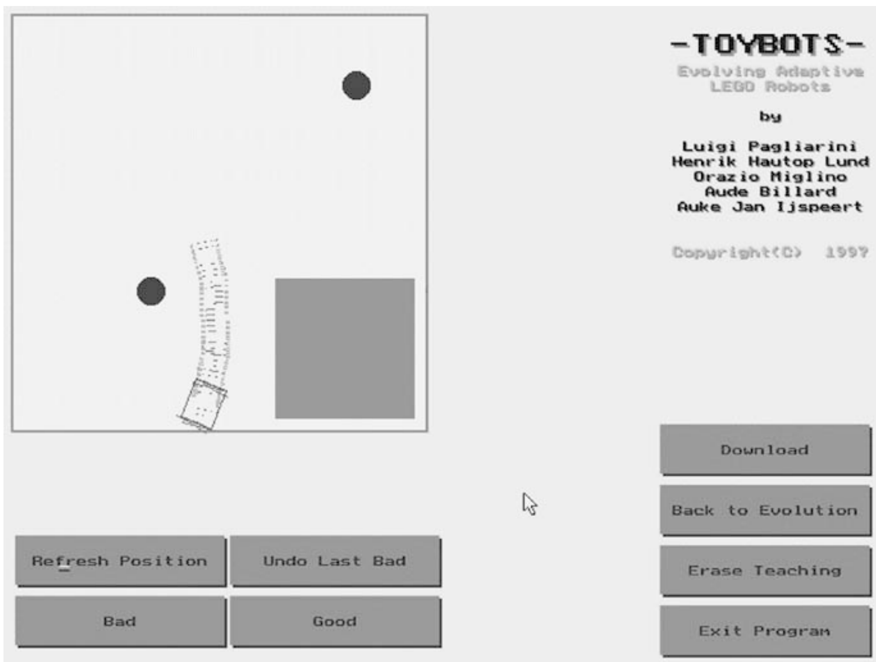

Fig. 3 A different aspect of the ToyBot model: the way in which learning can feedback into the evolutionary process producing what looks like Lamarckian evolution. This simulation applies user-guided reinforcement learning. The user selects one of the artificial organisms (from the whole population) and evaluates its behavior by clicking on the "bad" or "good" buttons. This causes the controller (i.e. the neural network) of the organism to be either modified or consolidated. Here, too, the changes introduced by the user will, in the end, generate satisfactory behavior

which could then be reproduced; in the UGRL, on the other hand, the user picks one of the ToyBots and modifies its behavior by pressing either a "good" or "bad" button accordingly to the evaluation of the behavior displayed by the robot. Students were generally asked to develop simple behaviors such as obstacle avoidance, following or avoiding lines, attraction or fear of light sources, etc. It is worthy of note that in Toybots, unlike Face-It, there is no one-to-one genotype–phenotype mapping. Here, the mapping is one-to-many. This difference is easily "felt" by the user. Given, for example, that different organisms start their lives in different positions in the environment even robots with identical genotypes can produce different emergent behavior.

SURVIVE! Survive! (Pagliarini, Parisi 1996; Fig. 4) consists of a micro-world containing artificial organisms and pieces of food. The organisms, which are controlled by small neural networks, navigate in this environment. When an organism reaches a piece of food, it eats and the food disappears. An organism reproduces (i.e. generates an offspring through asexual reproduction) when a certain number of food pieces have been eaten. If an organism lives for a long period without eating it dies. During the game the only thing a player can do is to administer a container of food resources so as to keep the population alive as long as possible. The game constantly informs the user of the best results achieved so far (i.e. the longest time a population has been kept alive). When the amount of food in the environment increases, the population grows. When it is

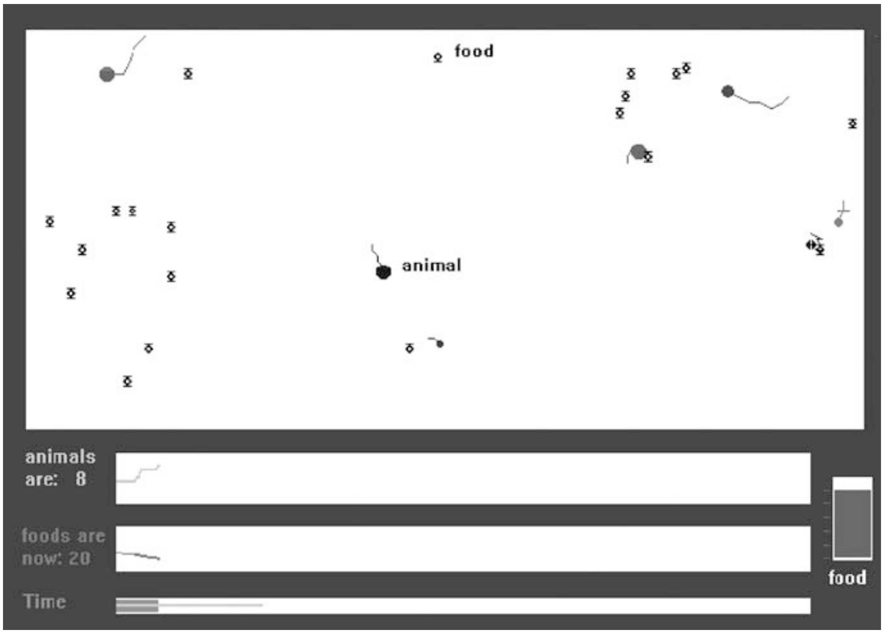

Fig. 4 Survive! focuses on the concept of natural selection. A population of artificial organisms evolves on-line. The user administers a food container, releasing food into the environment by clicking the mouse. The goal is to allow the population to survive for as long as possible

insufficient the population falls. It is very hard for the user to determine the rate of food delivery which optimizes the population survival time.

The tool was originally designed to help children understand key topics in ecology such as energy management and population dynamics. Given, however, that it allows the user to manipulate just one variable (the quantity of food in the environment) we believed that it would also be an effective tool to introduce and explain Darwinian concepts such as natural selection and fitness, which were dealt with only in part by Face-It and Toybot.

It should be noted that Survive!, unlike Face-it and Toybot, allows users to modify the environment (i.e. by releasing more or less food over a given period of time), but does not allow them to take any action which favors any one particular organism in the selection process.

Results

The performance achieved by the experimental and control groups is shown in Fig. 5. As can be seen, both groups started with the same level of knowledge. ANOVA on the questionnaire administered before the lesson shows no significant difference in the performance of the two groups ($F_{1,21} = 3.8$, $P > 0.05$). Both groups improved their performance after the teachers lesson (applying an ANOVA test–retest analysis to the performances achieved before and after the lesson, we observed $F_{1,21} = 4.68$, $P < 0.05$ for the "hypertext" condition, and $F_{1,21} = 4.89$, $P < 0.05$ for the "artificial life" condition). Following the software sessions, the students achieved a further increase in their performance (an ANOVA test–retest analysis on the questionnaire results before and after the software session, gave $F_{1,21} = 5.02$, $P < 0.05$ for the "hypertext" condition, and $F_{1,21} = 5.23$, $P < 0.05$ for the "artificial life" condition). "Artificial life" users scored significantly higher marks than "hypertext" users ($F_{1,21} = 5.78$, $P < 0.05$).

Discussion and conclusions

The results of our work show that complementing traditional teaching with other educational tools (in this case hypertext and artificial life software) can have a significant effect on learning performance. This result is in line with the results of numerous other studies in which new educational tools are combined with standard teaching. The most interesting result of our work, however, is that students who use artificial life software achieve greater improvements in performance than those who use hypertexts.

The observed improvement in performance over time suggests that doing experiments helps learning. We cannot however rule out the possibility that the observed effect was simply due to the extra time spent on the subject. In future studies it would be useful if a control group took additional traditional lessons for a time equivalent to the duration of the software session. It should be noted, nonetheless, that the software sessions using artificial life software were significantly more effective than those based on hypertext. Artificial life software allows users to be actively involved in conducting experiments. In hypertexts on the other hand users play a more or less passive role and have no opportunity to do hand-on work. The results of our work suggest, therefore, that experimentation should be included as a supplement to standard lessons using textbook material. It should be recognized, nonetheless, that these results are only a first step towards quantifying the effects of artificial life software in education (and more in general computer simulations). In future studies more extensive measurements will be needed. To generalize our results it will be necessary to design experiments which control, possible confounders such as gender, age, different cultural levels, etc.) that may affect the learning process.

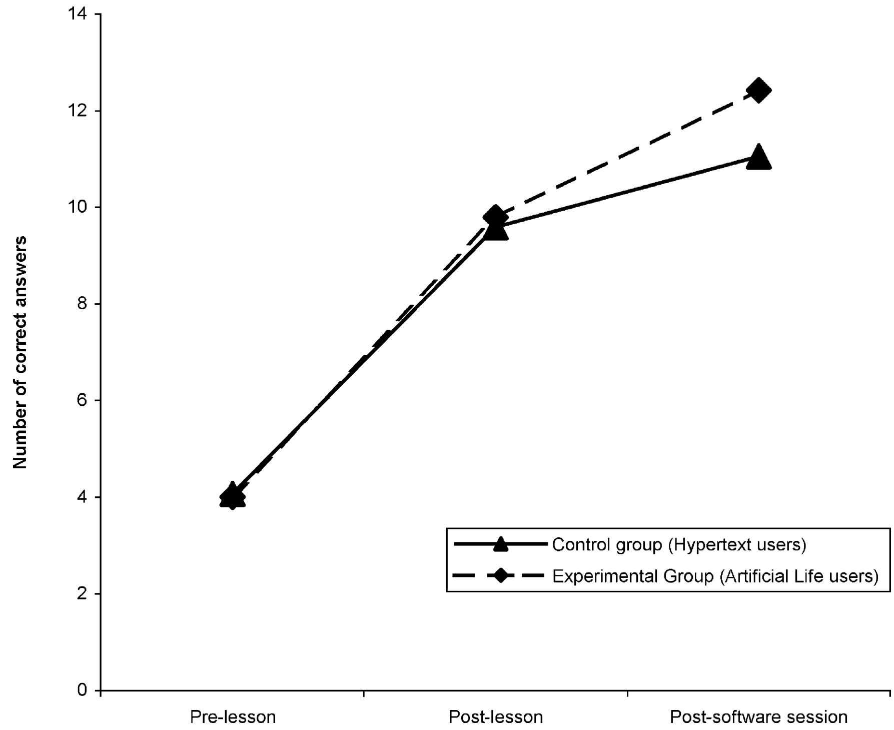

Fig. 5 The graph plots the average performance of the control group (*solid line*) and the experimental group (*dotted line*) over time. The subjects were tested using a questionnaire on evolutionary theory. The questionnaire was administered three times: before a standard lesson, after the lesson, and once again after using either a hypertext tool (control group) or an artificial life tool (experimental group)

On the basis of our experience to date, we can make three (rather obvious) recommendations concerning the use of artificial life for education:

1. the use of the software should be embedded in the standard curriculum, as laboratory work associated with standard lessons;
2. in experiments it is preferable to manipulate just a few variables, so that the user can understand specific effects;
3. it is best to avoid software that allows a high degree of creativity. While manipulating many variables may be creative it can lead to loss of focus reducing the educational value of the activity.

More generally we suggest that artificial life techniques and models could play a key role in the design of future e-learning products. Integrating textbook contents, traditional multimedia techniques (hypertext, animation, sound, etc.) and artificial life simulation tools could produce a electronic environment where passive learning (based on reading, watching and listening) is "contaminated" by elements of active "learning by doing".

Appendix I: Questionnaire on basic notions of Darwinian theory

1. The theory that states that species are static is called:
a) Creationism
b) Evolutionism
c) Fixism
d) Lamarckian

2. According to Darwinian theory:
a) current organisms arose via successive modifications of the genotypes of organisms living in the past
b) the morphological characteristics of organs evolved in response to their use
c) evolutionary history includes rapid change (i.e. evolutionary jumps)
d) current organisms arose from random mating between other organisms that lived in the past

3. A change in genotype structure that increases an organism fitness is called:
a) selection
b) mutation
c) adaptation
d) modification

4. Darwinian theory is defined as:
a) the theory of evolution via natural selection
b) the theory of evolution via the transmission of hereditary characters
c) the theory of evolution via artificial selection
d) the theory of evolution via the transmission of learned characters

5. Artificial selection is:
a) An evolutionary process that eliminates non-adaptive organisms and rewards the fittest
b) An evolutionary process driven by a breeder who selects organisms for reproduction
c) the struggle for survival
d) an evolutionary process that randomly selects organisms for reproduction

6. A modification in the genetic heritage transmitted by parents to their offspring is called:
a) adaptation
b) variation
c) mutation
d) heredity

7. The genetic program inherited from parents is called:
a) the phenotype
b) characteristics
c) the genotype
d) the soma

8. According to Lamarckian evolutionary theory organisms inherit:
a) their parents' genetic heritage only;
b) somatic characteristics acquired through interaction with the environment
c) both their parents' genetic heritage and somatic characteristics acquired through interaction with the environment
d) random genetic characteristics from their parents

9. The interaction between an organism's genetic heritage and the environment produces:
a) the genotype
b) adaptation
c) mutation
d) the phenotype

10. The evolutionary process that, in the wild, chooses the fittest organism is called:
a) cloning
b) natural selection
c) artificial selection
d) cross-over

11. According to Darwinian theory:
a) organisms inherit their parents' genetic characteristics
b) organisms inherit only those characteristics that have emerged from natural selection
c) phenotypic diversity within a species is not random
d) the only characteristics which organisms inherit from their parents, via natural selection, are adaptive characteristics

12. The process that produces an organism identical to its parent is called:
a) mutation
b) cross-over
c) selection
d) cloning

13. Is it possible that different genotypes can produce the same phenotype?
a) yes
b) no

14. Is it possible that organisms with the same genotype can have different phenotypes?
a) yes
b) no

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