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RESEARCH-BASED TEACHING ABOUT BIOLOGICAL EVOLUTION

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Abstract

This paper reports an attempt to design a teaching-learning sequence in which the students are stimulated to construct a scientific model of evolution, and to use this model in various contexts. Theoretical reflection, instructional design and classroom research have been linked in a cyclic process of development. Basic principles in the sequence were to make the students aware of different ideas about evolution, both scientific and "alternative" ones, to encourage them to reflect on their own thinking, and to use group discussions as a tool for effective learning. A group of 18 students, all at the age of 17, were followed during a 16-hour unit on evolution. The sequence was evaluated both in terms of the students' learning and in terms of their experience of the teaching. The results from a delayed post-test, about one year after instruction, show that most students had abandoned pre-instructional "alternative" conceptions, in favour for more scientific ones. As judged from logbook entries, a vast majority of the students also appreciated the teaching approach during the unit, and some students spontaneously expressed their satisfaction with being able to use the theory of evolution as a scientific tool.

1. Introduction

Evolutionary theory is nowadays generally considered to be a cornerstone in the science of biology and it provides a unifying framework for most biological knowledge. This makes the theory of evolution necessary for a sound understanding of biology and implies that it should be an important part of biology education. Although the basic principles of the theory of evolution have been described as logical and obvious (Mayr, 1997), many students have problems in grasping them. A major reason for these problems might be that its principles may seem counter-intuitive, both in relation to the students' own experiences of biological phenomena and to the everyday language used to explain these phenomena.

Research on teaching and learning science has for some decades been dominated by investigations on students' conceptions, first on the content level and later also on meta-levels, e.g. conceptions of learning and of the nature of science. Thousands of studies on students' pre- and/or post-instructional conceptions from various scientific domains, including evolutionary biology, have been published (see Pfundt & Duit, 2000). The studies on "alternative" conceptions have to a large extent been embedded in constructivist theories of learning, often inspired by Jean Piaget and with a focus on the individual learner. The major teaching approaches derived from this individual constructivist perspective are based on conceptual change (Posner, Strike, Hewson & Gertzog, 1982; Strike & Posner, 1992), and seem to have been more successful than traditional teaching. However, the classical conceptual change approaches have been criticised, both for being too rational and thereby paying to little attention to e.g. affective and motivational aspects of learning, and for leaning too one-sidedly on an individual constructivist epistemology. As a response to this criticism there has been a movement for merging individual and sociocultural perspectives on science learning and teaching (Hewson, Beeth & Thorley, 1998; Duit & Treagust, 1998).

This paper reports an attempt to design a teaching-learning sequence on biological evolution, which enables the students to construct a scientific understanding of biological evolution and use the theory of evolution in various contexts. The design draws, in a pragmatic way, both on knowledge about students' "alternative" conceptions and learning problems in this subject content area, and general teaching recommendations derived from different theories of learning. Previous research, and teachers' professional knowledge, on the teaching of evolution was also used to inform the design. Theoretical reflection, instructional design and classroom research was linked in a cyclic process of developmental research (Lijnse, 1995).

1.1- Conceptual analysis

The basic idea of the theory of evolution arises from three premises: 1) Organisms tend to produce more offspring than can survive. 2) There is inherited variation between offspring. 3) Some variations are beneficial to its carrier. As a result, the proportion of individuals with advantage-giving characteristics will increase in a population. This chain of thoughts is rather close to Darwin's own argumentation before he coined the term: "I have called this principle, by which each slight variation, if useful, is preserved, by the term Natural Selection" (Darwin, 1859). During the twentieth century genetics was incorporated into the theory of evolution in what is called "the modern synthesis" (Futuyma, 1998), and biological evolution is since then usually seen as a change in the proportions of genes in the gene pool of a population.

For educational purposes the points above have been rewritten into five principles (Ferrari & Chi, 1998). These principles were focused in the teaching-learning sequence, and also served as a template for assessing student responses:

1. Individual variation (variation)
2. Differential survival rate (survival)
3. Genetically determined heritability (heredity)
4. Differential reproduction rate (reproduction)
5. Accumulation of changes (accumulation)

In addition to these principles two other concepts are of basic importance and will be emphasised in the sequence; mutations as the ultimate origin of new variation and the concept of common descent, with the evolution of life depicted as a branching tree.

1.2- Students' pre-instructional conceptions of evolution

A number of studies have shown that students from different countries share a number of common conceptions of evolution, which are not consistent with biological knowledge (see Wallin, Hagman & Olander, 2001, for overview). These studies show that students often have an intuitive and undeveloped view of evolution, which makes them unaware of some of the more important principles of the way evolution works. For example, the process of evolution is often conceptualised as one single process in which characteristics of the species change gradually (Bishop & Anderson, 1990). The scientific view recognises (at least) two separate processes. The origin of new traits is a random process that generates genetic variation, and the survival of these traits is a non-random process, which decreases genetic variation within populations, basically by natural selection.

Many students also have a typological view on populations, i.e. they consider the individuals in a population to be virtually identical, and do not pay attention to the variation among individuals in a population. With this view natural selection does not work, and students tend to think that populations (or species) change because they need to change (Greene, 1990). Although many students probably consider evolution to be a need-driven process, the frequent use of the word *need* in the context of evolution doesn't necessarily mean that they have misunderstood the evolutionary processes. It is possible to express oneself in the words of need and still have a sound understanding of evolution (Wallin et al., 2001; Southerland, Abrams, Cummins & Anzelmo, 2001). Furthermore, evolution is often seen as just a gradual change in the traits themselves, instead of mainly as a change in proportions among individuals with different traits (Brumby, 1984; Bishop & Anderson, 1990). All of this is closely related to the conception that evolution is caused by individuals adapting to their environment.

In many cases evolutionary theory uses a terminology that is confusing for students. The evolutionary meaning of the word *adaptation* has, for example, proven difficult for students to capture. One reason for this is probably that the everyday uses of this word contradict its evolutionary significance. By applying the everyday meaning of adaptation in evolutionary contexts the notion of individual adaptation is enforced. *Fitness* is another word with multiple meanings, which is troublesome for students. In evolutionary theory it is defined as an individual's reproductive success, but many students have problems connecting natural selection with reproduction success. They often tend to discuss fitness and natural selection only in terms of physical fitness and survival.

Thus, the main "alternative" conceptions a teacher has to face are a) evolution as one single, gradual process, b) a typological view of populations, c) need driven evolution, d) individual adaptation. Furthermore, everyday interpretations of terminology have to be considered.

1.3- Evaluations of teaching on evolution

A few specially designed teaching strategies, mostly based on constructivist views on learning, have been reported to give slightly better results than "traditional teaching". Bishop and Anderson (1990) noted that the use of specially designed materials during one week of instruction in a college course was moderately successful in improving students' understanding. However, a later replication of this study could not show any difference between conceptual change and traditional teaching (Demastes, Settlage & Good, 1995). They suggested that time is a limiting factor and that the teachers epistemological beliefs are important. Jimenez-Aleixandre (1992) describes a conceptual change strategy, to Spanish 14 year old pupils, that gave better results than traditional teaching. The main features of the strategy were that it focused on the pupils' own ideas and that the students were given plenty of opportunities to discuss and work with them and compare them with scientific ideas. Jensen and Finley (1996) used a somewhat similar approach, and showed that the use of a historically rich curriculum, which explicitly addressed different ideas of evolution, combined with paired problem solving was slightly, but significantly, more effective than traditional (didactic) teaching in improving the students' use of Darwinian explanations. However, the time period during which evolution was taught was rather short (about 6 lessons during one week), and the authors conclude that further studies are needed in which the students are given more time for learning evolution.

The conclusion from this is that previous evaluations indicate that the teaching of evolution needs a considerable time to give acceptable learning outcome, that it is important to engage the students in active work with different ideas, and that the teacher must be familiar with the basic ideas of the teaching approach.

1.4- Aims of the study

The main purpose of this study was to gain insight in how research can improve teaching and how students respond to a research based teaching-learning sequence. To achieve this the outcome of the sequence was evaluated, in terms of both the students' content knowledge and their experience of the sequence, and discussed in relation to the teaching.

2. Methods and samples

The teaching-learning sequence described in this paper was designed for a compulsory course in biology (Biology A) in the Natural Science Programme at upper secondary school in Sweden. This course comprised 50 hours of teaching and covered mainly ecology, ethology and evolution (Skolverket, 1994). Evolution was strongly emphasised in the curriculum of the course, and we used 16 out of the 50 hours exclusively for teaching evolution. These 16 hours were divided into 9 lessons and a 3-hours written exam. After the return of the exam the students were given the opportunity to evaluate and comment on the whole unit. The specific content and activities within the unit were based on two pilot studies, literature studies and the national curriculum for the course. Both the general outline of the sequence and the detailed plans for each lesson were discussed thoroughly by the research team. All lessons were taught by one of the authors (CO) and were observed and videotaped by another (AW), who also took field notes. The outcome from each lesson was analysed and assessed in a formative way, in tape-recorded meetings, so that the plans for the next lessons could be adequately modified. The general design of the study is shown in figure 1.

Sept. 2000	Nov. - Dec. 2000		Dec. 2001
Pre-test	Teaching sequence	Exam	Delayed post-test

Figure 1. The design of this study.

2.1- Students

A group of 18 students (13 males and 5 females), all at the age of 17, were followed during the unit on evolution. They attended a school in central Göteborg, but most of them came from areas around the city. Most of them are ethnical Swedes and, due to the reputation of the Natural Science Programme to be highly demanding, can be described as well motivated and talented. All of them gave written agreements to participate in the study

2.2- Tests

Students' prior ideas were investigated by a pre-test (Göteborg University, 2000a), which to some extent became part of the instruction, e.g. in structured small group discussion and as starting points for discussions in class. The pre-test consisted of nine problems, some open-ended but mostly multiple-choice, and were given about two months prior to instruction. Since we were particularly interested in long-term retention, the students were also given a post-test, approximately one year after the teaching-learning sequence. This post-test was essentially identical to the pre-test, except for one problem, which had been added (Göteborg University, 2000b). It is a risk that the use of similar pre- and post-tests might lead to an overestimation of the learning outcome, but it was believed that the long time between the tests reduced this effect significantly.

Problem 2

Cheetahs are able to run fast, around 100 km/h when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could only run 30 km/h?

Problem 3

A number of mosquito populations are today resistant to DDT (a chemical used to kill insects), so that DDT treatment now is less effective than it used to be. Biologists believe that the DDT resistance evolved because:

1. Individual mosquitoes developed resistance to DDT after being exposed to it.
2. The mosquito populations needed to be resistant to DDT in order to survive.
3. A few mosquitoes were probably resistant to DDT before it was ever used
4. The mosquito populations became resistant by chance.

Problem 4

Throughout time living organisms have developed a variety of different traits. What is the origin of this enormous variation?

1. The traits arose when they where needed.
2. Random changes in the gene pool of the organisms.
3. Living organisms strive to develop.
4. Great variation is needed in order to get balance in nature.

Problem 6

a) The trait of webbed feet in ducks appeared in their ancestors because:

they lived in water and needed webbed feet to swim. **1 2 3 4 5** of a chance mutation.

b) Why did you choose this answer

Figure 2. Four problems from the pre- and post-tests.

Seal problem
Seals can remain underwater without breathing for nearly 45 minutes as they hunt for fish. How would a biologist explain how the ability to not breathe for long periods of time has evolved, assuming their ancestors could stay underwater for just a couple of minutes?

Figure 3. The "seal" problem from the written exam.

The results from four of the problems that occurred in both pre- and post-tests (figure 2), and one of the problems from the written exam (figure 3), will be discussed in this paper. Problem 4 was specially designed for this project, whereas the other problems were adapted from the literature (Bishop & Anderson, 1986; 1990; Settlage, 1994; Jensen & Finley, 1995). Both the pre- and post-tests were distributed over the Internet, so the students answered the tests on computers and their answers were submitted directly to our database. It was made clear to the students that the pre-test should not have any influence on the grading and that their biology teacher would only be allowed to see the results from the pre-test at the group level. The written exam was given directly after the teaching-learning sequence and was of great importance for the grading of the students. The students answered these questions very carefully and often with rather long answers.

2.3- Categorisation, ranking and statistics

The answers to the "cheetah" problem in the pre- and post-tests were categorised according to which major type of explanation the students offered. The main categories were identified as "general development", "need", "acquired" and "natural selection". In order to assess the quality in more depth, and be able to compare to the "seal"-problem in the written exam, each answer was also given a rank, based on which of the scientific principles (variation, survival, heredity, reproduction and accumulation) they included according to table 1.

Table 1. Ranking of the cheetah and seal problems.

Rank	Principles
1	No response
2	Don't know/irrelevant
3	General development/need etc
4	General development/need etc + additional principle or scientific concept
5	Variation + Survival
6	Variation + Survival + additional 1 principle
7	Variation + Survival + additional 2 principles
8	Variation + Survival + Heredity + Reproduction + Accumulation

A total rank was determined for the pre- and post-tests for each student. This total rank was based on eight of the nine problems that were identical on both tests. One problem was omitted because it concerned the students' religious beliefs, rather than their knowledge on evolution. The multiple-choice problems were given ranks between 1 and 4, the Likert-type problems (including motivations) between 1 and 8, and the open-ended problems also between 1 and 8 (table 1). The possible rank of a whole test was thus between 8 and 52.

The students' pre- and post-test results were compared by a paired t-test. To test for the post-test results dependence on the pre-test result a regression analysis was done, and the coefficient of determination (R^2) was calculated. (Snedecor & Cochran, 1967)

2.4- Logbooks

The students regularly made logbook entries, in which they were asked to reflect on the different activities, on what they learned and on their way of thinking. The students were allowed to express themselves fairly freely. The response from the teacher was given orally and usually at group level, at suitable occasions during the following lesson(s). At the end of the unit they were asked for a concluding remark as a kind of evaluation. The logbook entries were used to assess the students' experiences of different parts of the teaching learning sequence.

3. The sequence

3.1- Content specific aims

Although the Biology A course was supposed to be a fairly high-level biology course, and the students could be considered to be both motivated and talented, we chose to put emphasis on basic concepts of the theory of evolution. The main objective of the unit was to "allow the students to construct a sound understanding of the theory of evolution". With this we mean that they should be able to understand the theory of evolution in a way that is in accord with the scientific view, to differentiate between scientific and "alternative" conceptions, and to use the theory of evolution as an explanation in new situations according to the principles outlined in the conceptual analysis. In this context we also emphasised the theory of evolution as a model, which the students were encouraged to use in different situations (Passmore & Stewart, 2002).

3.2- Teaching approach

The main purpose of this project was to design a teaching-learning sequence that "works" in practice, so it is to a large extent based on teachers professional knowledge and general recommendations derived from a variety of sources. However, the design also draws more explicitly on a combination of individual and sociocultural views on learning. We agree with Tobin and Tippins (1993), that the knowledge of students is "personally constructed but socially mediated", and emphasise the importance of social interactions for learning. The most distinguishing feature of the sequence was the many structured small group and whole class discussions. They were inspired by two different views on learning, and served two purposes, which was combined into a single strategy. One purpose, inspired by a sociocultural perspective on learning, (Vygotsky, 1986) was to allow the students to integrate the scientific language and their own everyday language, and to sharpen their ability to move between different discourses. We believe that this is of fundamental importance for the long-term retention of knowledge. Another purpose, inspired by the conceptual change model (Hewson, Beeth & Thorley, 1998), was to make the students aware of their own and their peers'existing ideas and compare those with the scientific ones. By articulating ideas and examine them critically, some ideas will lose in status, and others (hopefully the more scientific ones) will increase in status. In addition to the group discussions, some tasks were also specially designed to elicit metacognition, e.g. a computer based activity in which the students step by step had to reconsider their previous thoughts (Göteborg University, 2000c).

3.3- Teacher's role

The teacher has a central and important role in this teaching-learning sequence. He not only has to create a classroom atmosphere that is open and friendly and invites the students to express and discuss various ideas, but also to introduce and support scientific ideas in the classroom. Special effort was made to show the students that all contributions were taken

seriously. Much of the authority to decide what ideas that count as valid was handed over to the students, who were allowed to decide this for themselves on the basis of the explanation power of the ideas. All discussions, both in whole class and groups, had specific content aims and structured frames regarding time, number of students and material.

3.4- Lessons

Although the teaching-learning sequence was supposed to work as one integrated unit, with different parts intertwined, each of the 9 lessons had its own specific aim(s) (table 2). Lectures were kept short (usually not more than 20 minutes), and often with breaks for short small group discussions. The purpose of this was to initiate the process of internalisation of new concepts immediately (Olander, Hagman & Wallin, 2001).

Table 2. Main content in the nine lessons.

Lesson	**Short description**	**Duration** (minutes)
1	Historical perspective on thoughts of evolution (lecture) Basic genetics; DNA, inheritance and mutations (lecture) Origin of variation (group discussion)	120
2	Time; analogies (lecture) Timeline in the school's corridor (student activity)	80
3	Common descent, speciation, extinction (lecture) Origin of life (group discussion and computer activity) The giraffe's long neck (group discussion)	90
4	Role play with historical texts (student activity) Peppered moth (lecture) Natural selection game (student activity)	80
5	Nature of science: especially belief and science (lecture) Main strands of the theory of evolution (lecture) Chance: Yatzy (student activity) and "the eye" (lecture) Co-evolution (lecture and group discussion)	80
6	Organisation levels, example: sickle cell anaemia (lecture) Antibiotics resistance (group discussion), Reindeers legs (computer activity)	90
7	Evidence for evolution (lecture) Fossil reconstruction (student activity)	80
8	Speciation: allopathric and sympatric (lecture) Speciation of salamanders, Ensatina (student activity)	90
9	Significance of animal behaviour for survival and reproductive success: Fitness, animal behaviour and sexual selection (lecture) On which level of organisation do evolution work? (group discussion)	80

4. Results

4.1- Pre-instructional conceptions

The results on the pre-test were close to what might have been expected on basis of previous results, including our own results from previous rounds of the teaching-learning sequence (Wallin et al., 2001; Hagman, Olander & Wallin, 2001). Despite the limited reliability of a short pre-test, it is clear that our students entered the unit with a generally poor understanding of evolutionary theory and with frequent "alternative" conceptions.

For example, on the “cheetah” problem (see figure 2), only 28% of the students gave explanations based on natural selection, while explanations that were categorised as general development (some of which included the idea of individual adaptation) or need-driven evolution were common (Table 3).

Table 3. Student responses to the “cheetah” problem (problem 2), by category (n=18).

Category	Pre-test	Post-test
No response/irrelevant	1	0
General development	4	0
Need	7	2
Acquired	1	0
Natural selection	5	16

Also from the students’ responses to the other problems it was evident that the pre-instructional understanding of evolution was rather poor (figure 4, 5 and 6). Responses based on “individual adaptation”, “need” and “strive” were common.

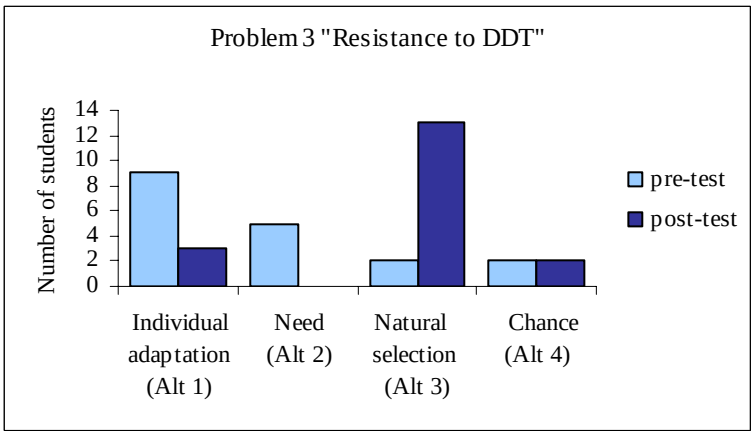

Figure 4. Number of students (n=18) choosing different alternatives on problem 3.

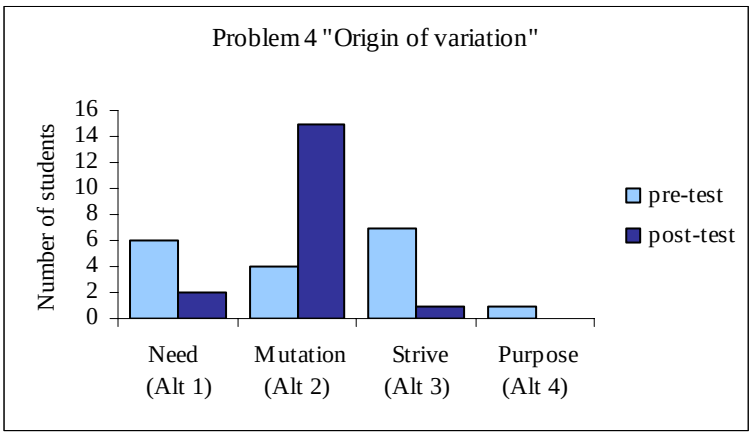

Figure 5. Number of students (n=18) choosing different alternatives on problem 4.

4.2- Learning outcome

A comparison of student responses between the pre-test and the delayed post-test reveals that most students had abandoned their pre-instructional conceptions of “individual adaptation”,

“need”, and “strive”, in favour of “natural selection” in problem 3 and in favour of “mutation” in problem 4 and 6.

On problem 6 (the “trait of webbed feet”) the students were asked to choose between two alternatives, based on “need” and “mutation”, respectively, on a Likert-scale, and also to motivate their choice. These motivations, which were categorized according to the acceptance of the “need”- and “mutation”- statements, corresponded well to the students’ choice on the Likert-scale. Some students accepted both statements, but in the post-test they used “need” in a way that was in accord with the scientific view. The number of students who gave motivations in accord with the theory of evolution increased from 2 in the pre-test to 14 students in the post-test.

In the open-ended “cheetah” problem (problem 2), an overwhelming majority of the students, (16 students) used natural selection in a correct sense in the post-test, compared to 5 students in the pre-test (table 3).

In the written exam, immediately after teaching; most students used scientific explanations in their answers. One of the tasks in the written exam (the “seal” problem) was comparable with the “cheetah” problem in the pre- and post-tests, and the rank of this problem was determined in the same manner (table 1). When the mean ranks on the ”seal” and “cheetah” problems are compared (figure 7), you can see an increase from 3.8 ± 1.6 in the pre-test to 7.1 ± 1.5 in the written exam, followed by a decrease to 6.6 ± 1.5 (mean ± s.dev.) in the post-test.

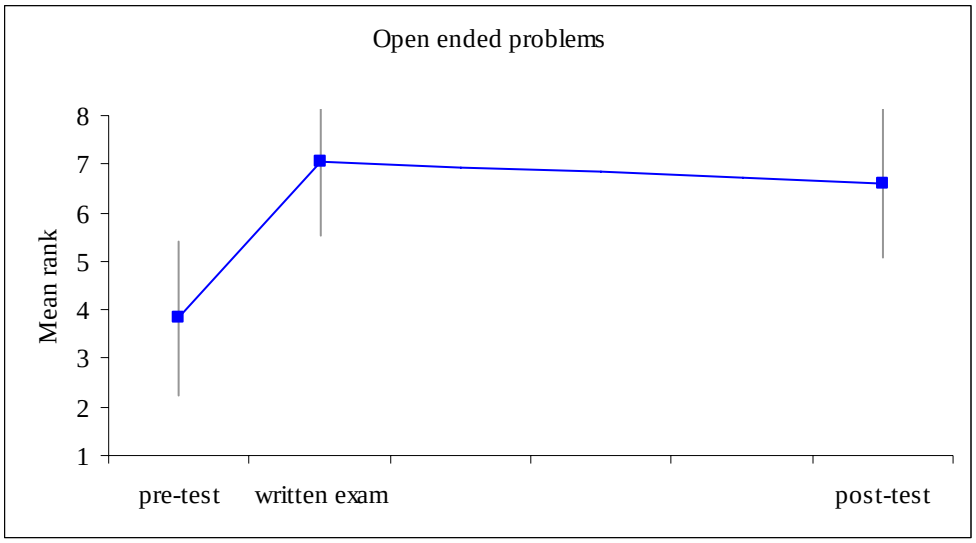

Figure 7. The mean rank of the “cheetah”-problem in pre- and post-test, and the “seal”-problem in the written exam. All the students in this study were included (n=18).

The students’ total ranks were higher in the post-test compared to the pre-test (figure 8). In fact all students in this study increased their total rank. The mean sum of rank increased from 26.2 ± 6.0 to 40.6 ± 7.9 (mean ± s.dev.). This increase was highly significant (paired t-test 9.5; df=17; p<<0,001).

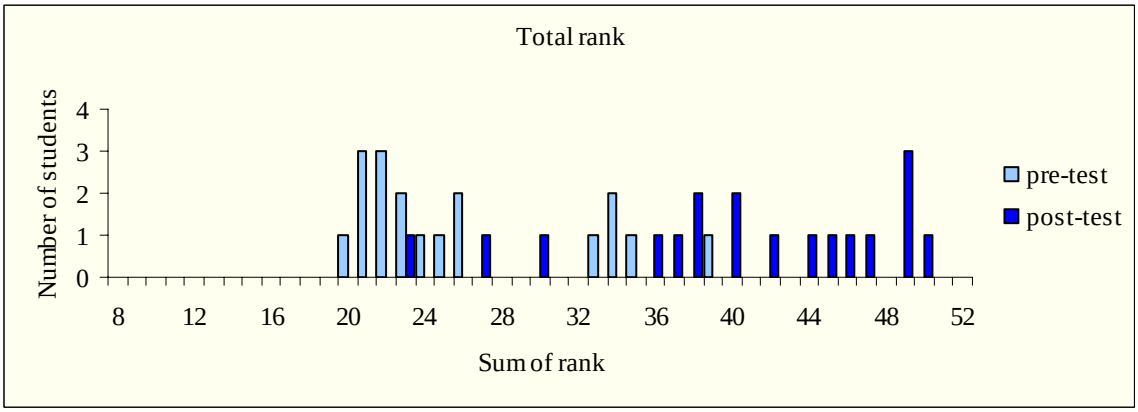

Figure 8. The students' pre- and post-test results (n=18).

To explore the effect of the students' pre-test results on the outcome of their post-test, a regression analysis was performed (figure 9). A linear model was applied with a significant result (F=9,1; p=0.008). This analysis indicate that about one third of the variation in the post-test results could be explained by results on the pre-test (R^2=0,36).

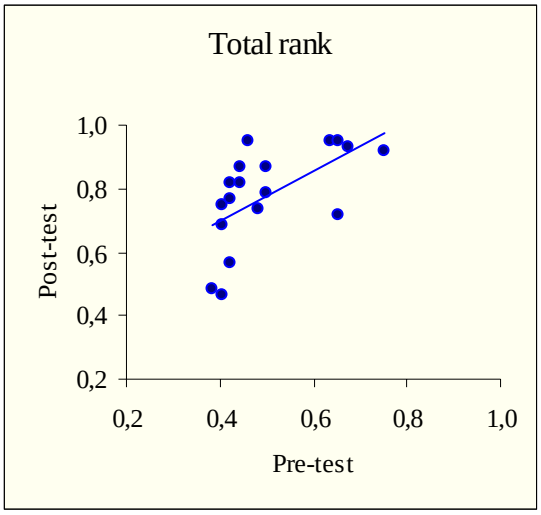

Figure 9. The students' post-test results as a function of their pre-test results (given as proportions).

4.3- Student attitudes and experiences

Analyses of the logbook entries show that most students' really appreciated the teaching approach during the unit. Fifteen of the 18 students were clearly positive to the teaching as a whole, and the other three did not express any opinion. The reasons for their appreciation can be divided into two main categories. 1) They enjoyed the teaching per se. 2) They appreciated the outcome of the teaching, i.e. they felt that they really learnt something in depth. One student expressed both these points very clearly in a concluding remark in the logbook: "*My honest opinion is that the evolution lessons have been interesting and fun. I have also learnt heaps of new things. And I really mean learnt, because I think this is something I'm gonna remember until I'm 80 years old!!!*"

The logbook entries indicate that the students found the classroom climate open and friendly so that they felt free to express their own thoughts. One student wrote for example: "*It's good*

that we can say and think whatever we like, and you don't get laughed at if you're wrong." This result is supported by the impressions of the observing researcher. The students also seemed to appreciate the discussions of different ideas (13 students expressed clearly positive evaluations), and found the many small group discussions stimulating and thought promoting, e.g. *"It was interesting to hear a lot of views which you could either reject, accept or develop", "Our `lets-take-a-few-minutes-and-think-of-this` discussions are really good! You have to think for yourself, it's necessary",* and *"I think our group discussions are good. You hear other people's ideas and exercise your brain"*. One student was sceptical to the discussions because he/she thought they were dominated by just a few persons.

Many students do appreciate the learning outcome of the unit, and they stress the difference between this teaching approach and their traditional teaching. They describe the teaching approach as "free", interesting or thought promoting: e.g. *"It's good with tasks in which you have to think for yourself, instead of just reading how it is", "I don't think I would have understood so much by just listening and taking notes. I think the good learning is due to all activities"* and *"All of this, that it is not just didactical teaching, is great!! Because that is soooooo boring!!!"* One student expressed a slightly different view: "*It would probably have been just as good with didactical teaching to me, but for a majority it was probably good*"

Some students even expressed the satisfaction with being able to use the theory of evolution as a scientific tool. Two examples: *"It was good with that internet thing about reindeers- You learn to think yourself, to use the theory of evolution."* and "… y*ou can use Darwin's theory on everything, that's nice …*".

5. Discussion

5.1- Learning outcome

The students' understanding of evolution did not only develop towards a more scientific level between the pre-test and the exam, but most of this knowledge also seemed to persist at the post-test one year after instruction. Furthermore, all students in this study improved their results from the pre-test to the delayed post-test. The decline in results between the written exam and the post-test is not very large. Considering that the motivation to give good answers probably was greater in the written exam, since the results of this was used for grading the students, while the post-test was not, the long term retention is remarkably good. We regard the learning outcome as satisfactory in relation to the content specific aims of the unit. Also in relation to the learning outcome reported in other studies, the results in this study appear to be relatively good. We can conclude that most of our students, after teaching, had a sound and long lasting understanding of biological evolution.

5.2- Student attitudes and experiences

The overall response of the students to the unit was very positive, especially on an affective and motivational level, i.e. they enjoyed the lessons and felt motivated to learn about the biological evolution. All students were not altogether positive. Some of them thought that there were too many group discussions and "games", that the same basic principles were addressed all the time etc. But the overall response to the unit was never the less very positive. This positive attitude might be due to our effort to create an open and friendly atmosphere in the classroom, which, according to logbook entries and field observations, succeeded to a considerable extent. Other factors may also be involved, e.g. that the students felt they really learned something (also supported by logbook entries), that the biological

evolution is a popular subject, or just the contrast between the teaching during this unit and their traditional, more didactical, teaching. We can conclude that the teaching during the unit was seen as meaningful and interesting to a vast majority of the students.

5.3- Learning as a result from teaching

All students in this study improved their results between the pre- and the post-test, albeit to different degrees. Although there was some correlation between the individual students' results on the pre-test and on the post-test, this correlation was mainly due to the students with the lowest rank on the pre-test. For students with average and above average results on the pre-test the results on the post-test seems to be independent on their pre-instructional knowledge.

If it is relatively clear that the students gained knowledge to a satisfactory degree, it is much harder to see what specific factors were crucial in the learning process. We can identify three main categories of possible learning promoting factors:

5.3.1- The teacher during this unit can be described as well informed about the subject content and the aims of the course, committed to the teaching approach and popular with the students. This had almost certainly a positive effect on motivation and learning, but we don't see it as a drawback in our study. The research question that remains to be answered in this respect is to what extent the "teacher factor" affects the learning outcome. It would be very interesting to try this teaching-learning sequence with other teachers in order to study to what extent "transfer" of teaching sequences is possible.

5.3.2- The general teaching approach, i.e. to build on ideas contributed by both the teacher and the students, and to express them and examine them critically, is appreciated by the students. Teaching ideas similar to ours have been tested elsewhere and often found successful (see Hewson *et al*., 1998), and, in the light of the learning gains reported here, this seems to be a fruitful approach also when teaching biological evolution. From the logbook entries it was obvious that at least some of the students shared this view, e.g.:

"Generally speaking, I think that the teaching has been good. Mostly because you have to do your own thinking and come to your own conclusions from what you've learnt"

There might, however, also be other factors contributing to the positive response, e.g. the very fact that there was research being done in the classroom. Although we tried to keep the "research factor" as low as possible (for instance that we did not perform any interviews, and that the observer had a very low profile in classroom), it is still possible that being the target of research stimulated the students.

5.3.3- The sequence: During the observations in the classroom some key points in this learning process were noticed. Already in a group discussion during first lesson, after instruction on basic genetics, it became obvious that the students readily abandoned "strive" and "purpose" as valid explanations to the origin of variation. Instead they chose between "need" and "mutation". Later, at the end of lesson 3, after further discussions of the origin of life and of different explanations to evolution, the "mutation" alternative had raised in status even more. Probably the importance of mutations in evolution is exaggerated in the students' minds at this time, but at least they seem to really have abandoned several "alternative" explanations to the origin of variation. Finally, during lesson 5, after the students had actively worked with natural selection, the observer noted that the students understood the random part

of evolution. Now it was clear to them that evolution consists of two processes and that only one of them includes chance, and during the remainder of the unit they had lots of opportunities to work with and strengthen this idea. Maybe this is the key to a sound understanding of evolution, as is suggested elsewhere (Bishop & Anderson, 1990), and our good long-term retention is dependent on successfully finding a way to solve the problem with the conception of evolution as one single process.

6. Conclusion

This study shows that you can design teaching that helps students to construct a scientific model of biological evolution. The design of this teaching-learning sequence was based on a combination of individual and sociocultural perspectives on teaching and learning, an approach that we found promising, especially regarding the long-term retention. We have been convinced that practice really can be improved by research.

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