HIGHER ORDER THINKING IN PHYSICS EDUCATION (HOT-PHYSICS)

Jens D. Holbech, Poul V., Thomsen, *Centre for Studies in Science Education, University of Aarhus, Aarhus C, Denmark*

1. Introduction

Denmark has 9 years of compulsory and comprehensive schooling (the "folk-school", 7-16 years of age). Integrated Science is taught in grades 1-6 for 1-3 lessons per week (each lasting 45 minutes) and integrated Physics/Chemistry is taught for 2 lessons per week in grades 7-9.

At the age of 16 the pupils have a number of possibilities for continued schooling and about 20% of the population choose the mathematics line of a general upper secondary schooling lasting 3 years (the "gymnasium"). In the mathematics line, physics is obligatory with 3 lessons per week for two years and optional in the third year (A-level: 5 lessons per week).

For a student the change from the folk-school to the gymnasium is a very real change since not only the physical surroundings change - the pupils also meet quite a different kind of teaching and of teacher: in the folk-school the teacher is trained at a teacher education college and familiar with (theoretical) pedagogy, but not so much with the subject. In the gymnasium the teacher has a master's degree from a university and is very well versed in his subjects (e.g. mathematics and physics) but knows little about pedagogy! Some of the problems and perspectives - especially students' interests and attitudes - connected to the transition from folk-school to gymnasium are demonstrated in Krogh & Thomsen (2001).

In this paper we address a quite different problem: the problem of missing thinking skills and how to treat it. In the folk-school, practical work and calculations of physical quantities are done on a regular basis but at a rather low level of abstraction (15 years ago this was different, but (unpublished) research showed the teaching to go far beyond students' possibilities for understanding and the curriculum was changed accordingly). From the first day in the gymnasium, however, the students are required to do formal thinking and manipulate formulas. This evidently can only succeed if the new students are carefully selected - but this is not the case. As a result, physics teachers have been complaining for years about falling standards.

2. Inspiration from CASE

Our inspiration for a project aimed at remedying the above problem came from the work by Shayer and Adey on the Cognitive Acceleration through Science Education (CASE)-project (e.g. Adey et al. 1995, Adey & Shayer 1994, Shayer 1999). Their work is aimed at students about 12 years old and based theoretically on a combination of Piaget's ideas of developmental stages (especially the transition from concrete to formal thinking) and Vygotsky's concepts of the 'zone of proximal development' and socially mediated learning.

Most students at that age are 'concrete' thinkers (level 2A-2B in Piagetian terminology) and the hope was through carefully planned instruction to induce students to progress to early formal thinking (3A) and beyond. For this purpose, the CASE team developed a teaching scheme consisting of a *concrete preparation* ideally leading to *cognitive conflict* and ensuing *construction of meaning*. This construction is stabilized by *metacognition*. The teaching scheme runs decoupled from the science lessons (*intervention lessons*) as independent 'thinking lessons', but during the following science lessons ample and explicit use is made of the (Piagetian) reasoning patterns introduced, e.g. *proportionality* and *control of variables*. Shayer and Adey claim striking successes and are especially proud of long term and far transfer effects as e.g. far better results in the experimental classes than in control groups at the nationwide GCSE examinations at age 16, i.e. 4 years after the intervention - not only in science, but also in mathematics and English.

3. The HOT-project

As mentioned above, about 20% of a Danish cohort enters the mathematical line of the upper secondary school and there are widespread problems with thinking skills. Our starting point was a reserved acceptance of Shayer and Adey's ideas - something like: 'it may work, so let's try. If it works: very good; if it doesn't: we got that wiser and we'll try something else'.
According to Shayer and Adey's early results (Adey & Shayer 1994, see also Shayer and Adey 1981), only about 5% of students around 16 should be late formal thinkers (3B) and another 25% early formal thinkers (3A). Even in the best case our target population would be dominated by 3A-students. This implies that the students may handle formulas but without a deeper understanding of what they are doing, e.g. considering $U = R \simeq I$, $R = U / I$ and $I = U / R$ as three different formulas (or prescriptions for use) instead of one; they may work with problems with two independent variables and control for factors explicitly named but not deal freely with multivariable problems; and they may do simple problems with constant ratios but are not able to do proportional reasoning - in short: they are not able to understand the concepts, the reasoning and the models required in the physics curriculum.
In order to find out the distribution of our students on Piagetian stages we used a translated version of the 'pendulum task' from the Science Reasoning Tasks (1992) which is a test of students' abilities to deal with control and exclusion of variables. In the very beginning of the HOT-project (Feb. 2000) we tested 4 classes, i.e. about 100 students, and convinced ourselves that most students actually handled control of variables at early formal level only. The teaching material was therefore designed to start at that level (or a little below) and aimed at lifting the students towards late formal thinking.

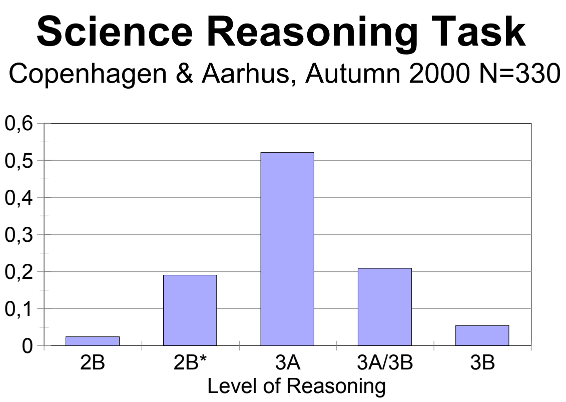

Figure 1: Initial percentages of students in Piagetian levels of reasoning.

Before starting the actual teaching in August 2000 we did the pendulum test on all 22 classes participating and on 15 control classes from the same schools. As described later, the actual course of the project was rather messy and only 7 of the classes tried more than half of the teaching material. We have only used these classes for statistics together with the control classes from the same schools (8), and Figure 1 shows the initial distribution of these 330 students on Piagetian levels. There are rather different distributions for each single class but no significant difference between experimental and control groups.

We had expected to do piloting of the material (to be described later) in just a few classes in our local area, but 10 teachers offered to try it out and the newly started Danish project 'World-Class Maths and Science' (www.matnatverdensklasse.dk) asked us to take a further 12 teachers from the Copenhagen area. The pilot phase thus comprised 22 classes with about 600 students.
The teachers were brought together at Aarhus University for two half-days during which they got an introduction to the thinking behind HOT-physics and the pendulum test. Most of the time was, however, spent on an introduction to the preliminary teaching material and discussions on its actual use and how to do the bridging to later physics lessons. One of us (JDH) taught a class himself using the HOT material and used the experiences to make a first adjustment. The adjusted material was immediately distributed via an Internet based conference where the participating teachers could also give their suggestions for changes, ask questions and initiate discussions.
Our original idea was that the HOT-lessons should be over before Christmas, but unfortunately this was not the case. Some of the teachers from the Copenhagen area only started in November because of simultaneous participation in another project under 'World-Class Maths and Science'. It also turned out to be more difficult to get feedback from the teachers about the working of the project.

The Internet conference was little used and we could only manage to have one or two short meetings (1-2 hours each) with the teachers. At the end of the school year JDH was the only one to have done all lessons and the most arduous teachers had taught about 75%, the least only about 25%.

At the end of the school year most classes - experimental as well as control - were tested again with the pendulum test. Due to the difficulties described above we were very modest in our expectations and we decided to look only at classes having trialled more than about 50% of the material and the control classes from the same schools. This gave us 7 experimental classes and 8 control classes. Also, we only used data from students having taken the test at the beginning as well as at the end of the school year and the net number of students then turned out to be 154 in experimental classes and 176 in control classes (these are the students behind Figure 1).

As mentioned, there were no significant differences between the two groups in the beginning of the school year, but there did turn out to be striking differences at the end of the year: the experimental classes had a significantly larger gain in reasoning level than had the control classes. To bring the results into a quantitative form we used the same numerical scale as Adey and Shayer (1994), i.e. 2B = 5, 2B* = 6, 3A = 7, 3A/3B = 8, 3B = 9, and it turned out that the initial value for Piagetian level was 7.07 .24 (corresponding to early formal). The control classes ended at 7.60 .27, i.e. an average gain of .52 ('half a level') while the experimental classes ended at a mean of 7.96 .38, i.e. an average gain of .91 ('nearly a whole level'). The difference between the gains is .36 corresponding to the experimental classes being 1.3 (control) standard deviations above the control classes. This is highly satisfactory (especially in view of our difficulties) but of course it is not clear whether it is due to the HOT-material or to the HOT-teachers (who joined voluntarily). The touchstone for this requires a much larger scope with participation of 'non-voluntary' teachers, but at least our initial hope is not falsified!

4. The HOT teaching sequences

In the CASE-project there are 32 intervention lessons distributed over 2 years. The lessons are designed to last for about 70 minutes each, i.e. a total of ~ 40 hours. The total amount of time for physics teaching in the first grade of Danish upper secondary school is 79 hours and it is quite clear that our ambitions about time consumption had to be at a much lower level than in CASE - maybe 15-20 hours in the best case. It was also clear to us that the HOT-lessons should be closer coupled to the physics teaching than were the CASE-lessons - partly in order for the teachers to feel comfortable about fulfilling their duties towards the syllabus, partly to have an opportunity to introduce the thinking skills before the students need them. Taking the speed of delivery in physics textbooks into account, this means that the HOT-lessons should be given during the autumn.

The thinking skills needed in the physics curriculum pertain mostly to using variables and formulas. We therefore chose – much along the same lines as CASE – to start with the concept of *variables*, *relationship between variables* and *control of variables*. Later on this was supplemented with *compound variables* (e.g. pressure, density), but in the meantime we did *ratios and proportionality* and *inverse proportionality ('compensation')* as an introduction to the use of formulas. Finally, we made lessons on *equilibrium* where connections and control of up to 4 independent variables come into play (a 3B-activity). We wanted also to include *modelling* – both as an independent lesson and as continuous input - but due to lack of time this never came into play.

A typical module follows the CASE teaching scheme with a *concrete preparation* where the teacher introduces materials and terminology and makes sure the students understand 'what it's all about'. This is followed by hands-on and mind-on activities where students work alone or in small groups with concrete material and/or worksheets (hopefully) establishing *cognitive conflicts* and a need for *construction of meaning*. The teacher has a central role as mediator and guide into the *zone of proximal development*[6] and peers have important roles too as sparring partners in discussions and as collaborators in trying out theoretical as well as practical suggestions for explanations and solutions. The newly acquired thinking patterns are used in a number of thought experiments and problems in order to consolidate them and further consolidation is aimed at through *metacognitive*

activities, e.g. students summing up and clarifying the new terminology, what they learned in the module, and how they learned it.
The teaching material consists of worksheets for students, concrete material for demonstrations and hands-on activities, and a teacher's guide with introduction to the theory and the aims behind the module, advice on actual teaching, and suggestions for bridging during the physics lessons to follow.
Space does not permit description of all these modules and we have to restrict ourselves to just one example: *control of variables*:
The module about control of variables followed a module on variables and relationship between variables: what is a variable, a variable may have qualitative or quantitative values, one may distinguish between independent and dependent variables, and finally some examples of qualitative relationships between dependent and independent variables.
The concrete preparation was a practical work with tubes (adapted partly from CASE, Activity 3: The 'fair test'). The tubes are of 3 different lengths, 3 different widths and 2 different materials. The teacher demonstrates the possibility of making sounds by tapping the end of a tube in a hand (in the first edition we asked for blowing across the tube, but one of the teachers informed us that tapping was much better than blowing and gave no problems with hygiene) and introduced the highness of the tone as the dependent variable wanted. Students were asked to try the tapping and afterwards identify the independent variables (length; width; material) and their values (long, medium, short; wide, medium, narrow; metal, plastic. Some students wanted to measure the lengths and widths to get quantitative variables and were allowed to do so).
The activity in the construction zone was for each student to pick pairs of tubes, compare the notes and try to find the relationship between highness of note and the independent variables. The students have access to all the tubes (the materials box contained 72 tubes of 18 different kinds) and get a worksheet asking the student to write down the combinations used and the conclusions drawn from the experiments: 'What is the influence of the width?', 'Which experiment tells you that?' etc. The teacher walks around and mediates cognitive conflict by asking for conclusions and challenging incorrect as well as correct suggestions: 'How can you be sure that width does not matter?', 'How can you be sure that only length matters?' 'Is one pair of tubes enough to draw a conclusion?' etc.
Some simple problems are given and the teacher initiates metacognition by asking the students to answer worksheet questions like 'What have you learned about control of variables when you have to find relationships between variables?' and 'How many independent variables must there be before needing control?'. Afterwards, a class discussion is organized about the topic and the students are asked to do a number of problems/thought experiments of increasing difficulty.
Suggested bridging during the physics lessons following the module is to explicitly ask students for control of variables in practical work, e.g. by planning experiments on Joule's law ($P = R \simeq I^2$) instead of giving them 'cookery book recipes'. Correspondingly, they may be challenged to 'construct' the equation of state for an ideal gas or at least to design experiments showing the effect of each variable on the other.

5. The future

At the brief meetings with the teachers we got very positive feedback about the teaching material and the modules they had tried out. They clearly saw HOT-physics as kind of an answer to at least some of their problems and they reported also about most students being very engaged in the activities which were at the right level for them to understand: considered as a teaching material (and looking apart from our ambitious aims) the HOT-modules were successful! The teachers strongly suggested us to continue.
In view of this we decided to run a second generation of HOT-physics - despite the messy way it had worked and despite the fact that we did not know at that time whether there were any positive effects. It was clear to us, however, that for methodological reasons we should prepare the teachers better and have a closer monitoring of the whole process.

We therefore advertised HOT-physics as an in-service teacher training course consisting of a 2-day introductory meeting in August 2001 (instead of 2 half-days) followed by one whole day late September and another late November.
The response was overwhelming: about 60 teachers wanted to participate, but we had to restrict ourselves to a doubling the course and could only accommodate 40 teachers (nevertheless corresponding to 10% of the first grade physics teachers in Denmark). A few of them had participated the year before, had been assigned to a new first grade class and wanted to try again in a more serious way. This of course is encouraging, but at least as encouraging is that most of our new teachers come from schools with teachers who participated the year before and had recommended the course.
At the time of writing we have just finished the two 2-day courses. As we hoped, they turned out to be much better and far more reflective than the stressful course last year and afterwards the participants were very keen to go back to their schools and do HOT-physics.
Whether the project will fulfill its aims is of course uncertain at the moment, but we think we have good reasons for optimism. But it *is* quite certain that about 60 physics teachers have been challenged to reflect on their former teaching habits, have experienced cognitive conflicts and made explicit decisions to change their practice. For the better, we believe, but time will show!

References

Adey P, and Shayer M, *Really Raising Standards,* Routledge, London, (1994).
Adey P, and Shayer M, Yates C., *Thinking Science* Thomas Nelson and Sons Ltd UK, (1995).
Krogh L and Thomsen P V, Teaching Style and Learning Outcomes, *Proceedings of GIREP-conference: "Physics Teacher Education Beyond 2000",* Elsevier, (2001), 257-260.
Science Reasoning Task III: The Pendulum Science Reasoning, 16 Fen End, OVER, Cambridge CB4 5NEShayer M Cognitive acceleration through science education II: its effects and scope *Int. J. Sci. Educ.* **21,** (1999), 883-902.
Shayer M and Adey P, *Towards a Science of Science Teaching,* Heinemann Educational, (1981).
Vygotsky L S, *Mind in Society,* Harvard University Press, (1978).