Tailoring Empirical Inquiry in Physics to Pupils' Needs according to their Knowledge about Density and Statistical Literacy

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***Abstract* – In this paper three orchestrations of the pupils' investigation concerning the concept of density are described. Three different groups of children (pre-school children, pupil of grade 2 and grade 4) were inquired about the differences of densities regarding the various kinds of candies. The substantial environment allowed an experienced teacher to tailor the investigations according to the needs, particularly the knowledge about density and statistical literacy of participating children.**

***Keywords* – Psychics education, math education.**

1. Introduction

Traditional transmissive "chalk-and-talk" methods of education have already been used for several decades [1]. Although Kirschner and Sweller [2] provided a thorough critique to all forms of education based on students' own investigations, particularly in mathematics, there are several studies describing benefits of student-centred approaches, mainly in deeper conceptual understanding and in the area of students beliefs, [3], [4] and analysing in depth various advantages of constructivist approach [5], [6].

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One of the main aims of education in science and mathematics is to motivate students through properly posed questions and problems. Students gain understanding, their imageries are developed and concepts become crystallized [7]. The reality of schools is often very different. Students are presented prepared facts which may lead to rote learning and acquisition of merely formal knowledge of concepts in mathematics and science [8], [9]. Teachers face a lot of issues and challenges when implementing constructivist approaches [10]. Teachers who lack experience with constructivist classroom often struggle with setting such a learning environment that is demanded for the constructivist perspective [11].

Constructivist education in science and mathematics can be implemented in the form of inquiry-based learning. Jaworski [12] sees inquiry as fitting with the constructivist view of knowledge and learning. Artigue and Blomhøj [13] define inquiry-based pedagogy "as a way of teaching in which students are invited to work in ways similar to how mathematicians and scientists work" and cite [14] the five essential features that can separate inquiry into full and partial inquiries: (i) pupils create their own scientifically oriented questions; (ii) pupils give priority to evidence in responding to questions; (iii) pupils formulate explanations from evidence; (iv) pupils connect explanations to scientific knowledge; (v) pupils communicate and justify explanations.

According to [15], the advance from experience to scientific empirical knowledge is a working method of experimental physics. They understand observations, measuring and experiment as enabling the scientists to obtain empirical data. Data are further processed by a theoretical method of knowledge, and they are then formulated in the form of an empirical fact. Handling the data is a competence which belongs to statistical literacy [16].

In Slovakia, the usual form of an experimental activity of pupils is organized in a logical sequence forming the following experimental method strategy presented by Koubek [17]. Each of the three main phases (thought preparation of cognition; material implementation of cognition; and thought processing of cognition) is divided into smaller steps (see Figure 1).

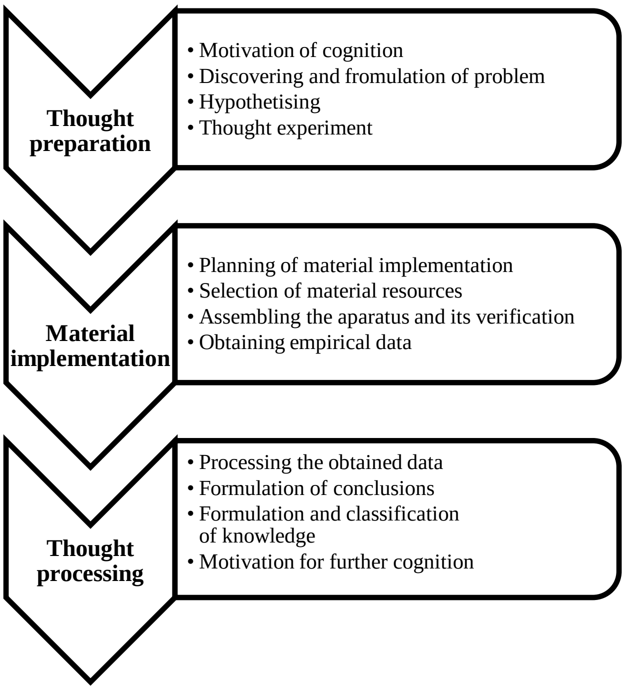

Figure 1. Model of empirical cognition in physics according to Koubek et al. [17]

The model of Koubek et al. is in accordance with the four-step model of statistical investigation proposed in [16] consisting of (i) posing a question; (ii) collecting data; (iii) analyzing the data and (iv) forming and conveying solutions. Since both authors are experts in statistics education, it is intelligible why they separated analysis of data and the formulation of conclusions.

It is generally understood that children often develop an intuitive sense of density long before it is taught in school [18]. They develop these intuitions from their observations in which solid objects can be the same size but have different weights and that very large objects can weigh less than much smaller ones [19]. Pupils' understanding of the concept of density should be developed through their experience with real objects. The situation with developing statistical literacy is essentially the same. Several authors, e.g. [4], reported better progress in mathematics when students developed their mathematical competencies trough the empirical activities.

Even though the school is traditionally structured around well-known subjects, including science and mathematics, it "does not necessarily mean that pupils' learning has to be restricted to working within these separate subjects, it can be substantially enriched by interdisciplinary work" [20]. By engaging with problems in meaningful contexts pupils can develop different skills and deepen their understanding of knowledge within the different subject disciplines [21].

The main aim of this paper is to provide the demonstration of the three different adjustments of physical investigation in the curriculum segment of density for pre-school children (age 5-6 years), grade 2 (age 7-8) and grade 4 (age 9-10) pupils and compare the manifested knowledge obtained by the participants.

2. The three orchestrations

The main topic of the investigation was the density of three different kinds of candies, particularly marshmallows, jellies and PEZ-like mints. Pupils should estimate which kind of candies would spill the highest amount of water out of the glass and give plausible reasoning to their answers. All the three orchestrations were based on the model of empirical cognition in physics [17].

The first author of the paper had a role of a teacher/mentor during all three described and analyzed sessions. The sessions were part of the long-term project within which the first author and other researchers regularly attended the classes and held different activities there, usually from physics. Thus we can conclude that all participating pupils considered the activities as a common part of their education. All pupils worked in pairs, as pair-work was the usual way of work during the sessions.

In case of pre-school children the activities were part of pupils' usual morning session in kindergarten. On the other hand, for the grade 2 and grade 4 pupils, the activity was out-of-school activity implemented in the school club after the regular lessons. 20 pre-school children, 18 pupils from grade 2 and 16 pupils from grade 4 participated in the sessions.

Participating **pre-school children** were included into game-like activity but they were aware that they were learning. The children were sitting by their usual desks in the classroom, the pairs were arranged by their usual teacher. The researcher told the children the story about mother who wanted to buy the candies for the party. She wanted special candies, candies which would spill the water out of the glass. Each child got a saucer for keeping the water, small plastic box with a string, small plastic glass for immersing the box with candies in water, glass for water, small transparent glass for recording the amount of spilled water and marker pen. Each group of students got a plate with different candies (jelly bears, other jelly candies, PEZ-like candies, and rocks candies). The given candies either sank or floated, pre-school children were not given candies that could hover in water.

The children said they have to make a "hill of water". Then they would put the box with candies into the glass and then found out how much water would be spilled. The "hill of water" is created by adding coins or pins to the glass of water full to the brim until the "hill of water" appears. Surface tension of water acts against the gravity and the water can go over the water without spilling. The procedure is described in more details in [22]. There was almost no space left in the boxes for candies. The children were motivated to put as much candies as possible to the boxes by promising them they could eat all the candies used for experimenting. Children did not want to eat the wet candies, so they tried to fill as much space as possible by the candies.

Firstly, children made the "hill of water" and then put the candies into the box. They quickly found out that they were destroying the "hill of water" by nudging the desks. So they first filled the boxes by candies and only then filled the glass by water up to the edge to form the "hill of water". Then they put the box with candies into the glass and observed how much water was spilled. Then the children poured the water from the saucer to the glass and marked the level of water. The same procedure was repeated with other types of candies. At the end of the lesson, there was whole-class discussion about the kind of candies mother should buy. The class prepared the poster (see Figure 2) summarizing the results of their activity.

The pre-school children were deeply involved in the investigations. They found that some of the candies sank and some floated. All the physics concepts were new for children, but all the participating children were able to conduct the experiment. As the children could not write, they recorded the measurement only as the marks on the "measuring" glass. They used marker pens of different colour to record different kinds of candies. In the end they compared the marks and ordered the candies according to the amount of spilled water.

The school pupils worked with graduated cylinders and electronic scales. The activity was intentionally implemented when the participating pupils worked on biology topic in their compulsory science.

Pupils of **grade 2** were not familiar with the concept of density from their previous schooling. Similarly to the pre-school children, the second-graders were not able to work with graded cylinders. The session started by experiments with surprising results to create the culture of investigations and inquiry. Some of experiments conducted with pre-school children earlier in the project were chosen. The pupils were introduced to the "hill of water" and they work with opaque plastic boxes which floated, hovered and sank. The main difference between the pre-school and grade 2 pupils was in four aspects. Firstly, the pupils first weighted the candies and tried to predict-test-explain the results. Another difference emerged from pupils' ability to write. So, we were able to provide the pupils by the worksheets (Appendix A) in which they could record their measurements. The children at this age are usually not able to work with tables [23], so the pupils were instructed to record the level of water in the picture of graduated cylinder. Worksheets provided mentors by more detailed and understandable feedback, comparing to pre-school children.

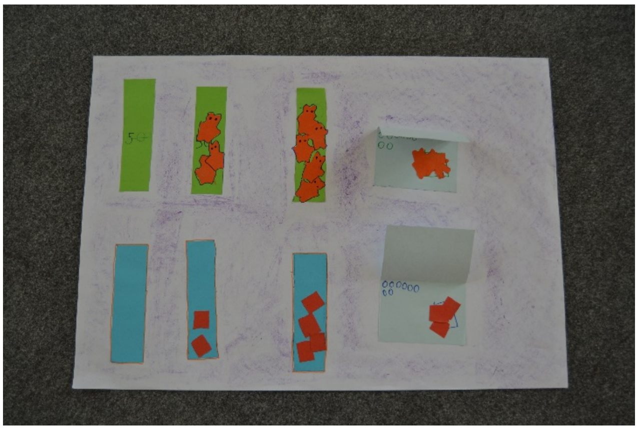

Figure 2. Poster designed by the participating pre-school children

The last stage of experiment when the candies without the plastic boxes were put into the graduated cylinder can be considered as a third difference. The pre-school children always put the candies in boxes. As the pre-school children compared the candies, the difference density caused by the small amount of water in boxes could be disregarded. The last difference was in the classroom management. Pupils could choose whether they will work in pairs or individually. Ten of the pupils chose to work individually, the other eight pupils formed four pairs, so the mentor got together 14 filled worksheets.

The work in **grade 4** differed because we expected the previous knowledge about the concept of density, as this is planned in grade 3 in national curricula. The experiments started with experiments about density, to refresh pupils' memory. Two 200 g objects were shown to pupils, one was the package of EPS marbles and the second was a weight. The procedure to find out the density of candies was not told to pupils, they were expected to come with their own suggestions.

All pupils worked in pairs. Pupils used scales and graduated cylinders. They refused to use transparent plastic boxes. Most of the pupils poured some (usually 30 ml) water into a graduated cylinder and tried to find out how many candies they could put in the cylinder until they reached a given (usually 50 ml) level of water. At the end they took the candies and weighed them. Some other groups took the given amount of candies and measured the level of water after putting the candies into the graduated cylinder. Pupils use the same worksheet as grade 2 pupils to record their measurements.

Both primary pupils (grade 2 and grade 4) should draw what will happen when the candies are put into the aquarium.

3. Findings and discussion

After four months, the **pre-school children** were subjected to the verification of the obtained knowledge. The empty opaque plastic box was put into water and children should give the reasoning why it was floating. They said that “there is air, similarly to the marshmallow, so it floats like the marshmallow”. We concluded that they were able to abstract the fact the air is lighter than water and therefore things contained air float. This observation is in accordance with children experience with e.g. inflatable toys floating on the water in pool. After children gave the correct reasoning, the researcher put into the water the same-looking box, but the box sank to the bottom of the glass bowl as it contained a weight. Children expected that heavy candies were in the box. In case of hovering box the children said that the box was neither empty (because the box did now float) nor containing heavy candies (because the box did not sink). One child said “there is something there but not the heavy candy because the box does not sink”.

Unlike the pre-school children the **pupils of grade 2** did the observations of the opaque plastic boxes before the experimenting with candies. They were encouraged to use the predict-test-explain approach. As they were already familiar with numbers, they recorded the level of water in the graduated cylinder (see Figure 3). In the four worksheets the same volume was recorded for all the types of candies (see Figure 4). None of the participating pupils was able to estimate the volume of candies as the difference between the two water levels and record it to the worksheets. They recorded the number of candies and their mass.

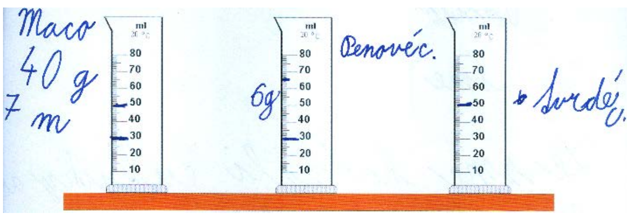

Figure 3. Correct recording of the volume of water in the two graduated cylinders on left

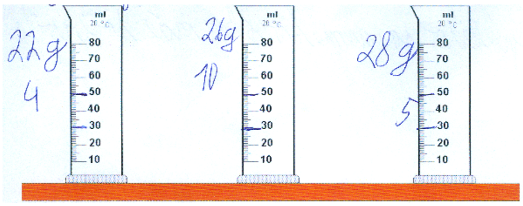

Figure 4. Incorrect recording of the volume of water in the graduated cylinders

Only one pair of pupils was able to predict the behaviour of the candies in the aquarium. Seven worksheets contained drawings where the candies were stacked in the form of tower. In four of the seven cases (see Figure 5) the candies even started from the very bottom of the aquarium. In three of these four cases the candies exceed the water level (see Figure 6). The pupils brought their experience from limited space in a graduated cylinder and did not take into account that the aquarium is wider than the cylinder. The other five worksheets contained drawings of hovering candies, but none of them were ordered according to the densities of the candies.

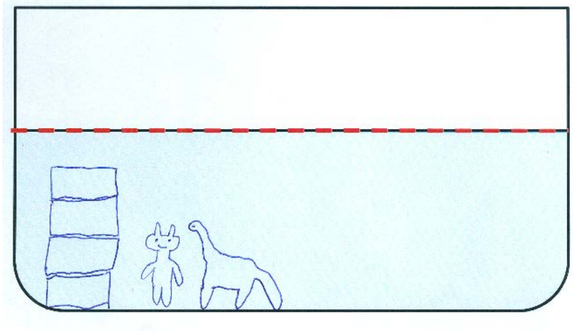

Figure 5. Gummies and rock candies stacked to the form of tower from the bottom of the aquarium

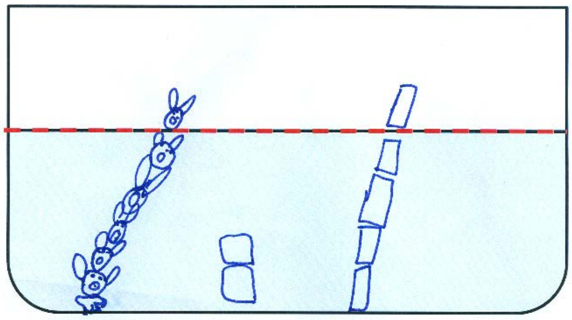

Figure 6. Gummies and rock candies stacked to the form of tower, from the very bottom and exceeding the water level

The worksheets were filled out during the activity as a laboratory sheet. Thus, they do not reflect the knowledge obtained and categorized during the finalizing whole-class discussion. With the help of an experienced teacher pupils of grade 2 were able to come up with reasoning why the candies could not be stacked, which of them would sink, which would hover and which would flow.

The participating **pupils of grade 4** gave considerable attention to the accuracy of their measurements, took detailed notes recording their work using the given table. They noted not only the numbers, but also their remarks. All the pupils still put the numbers next to the pictures of graduated cylinders and not to the table, similarly to grade 2 pupils. Two pairs of pupils did not record any volume in their worksheets. Two worksheets contained recordings of outcomes that definitely could not happen. Only four of eight worksheets contained numbers in the given table, the other groups used the table for recording their observations. Furthermore, the records in the table were only partially correct (see Figure 7).

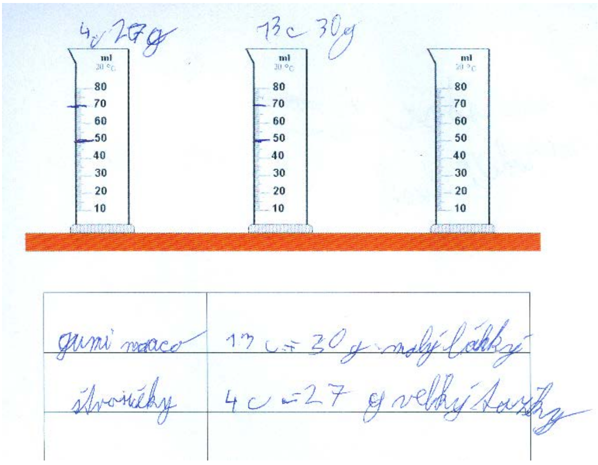

Figure 7. Table used for recording the numbers, not only the remarks

One pair of pupils gave the correct solution without any commentary. They drew exactly the candies they had worked with, including the flavour and package (see Figure 8).

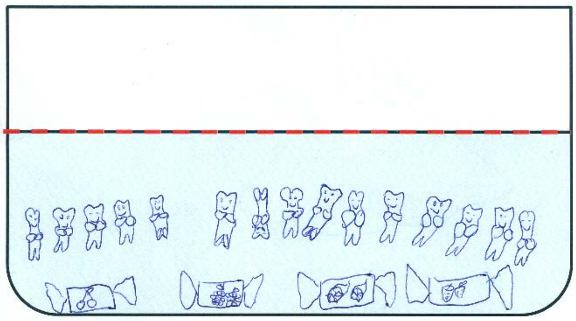

Figure 8. The detailed correct solution

The three solutions were principally correct and commented „they fell accurately on top of each other, they hovered a bit and sank a bit [oni padali úplne na seba, aj trochu sa vznášali, aj trochu padali]“ (see Figure 9). If the pupils had drawn only one candy of each kind, it would not have been possible to see the misconception. As the pupils put several candies to graduated cylinders, they tended to draw more than one candy in the worksheet.

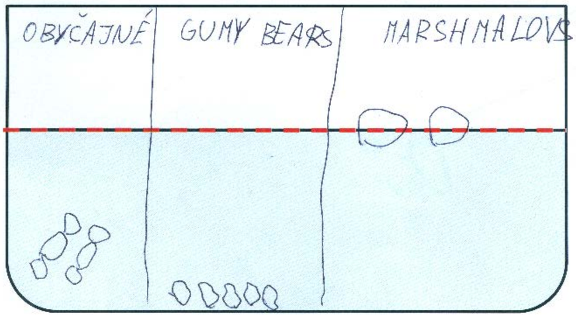

Figure 9. Partially correct solution

Five pairs of pupils only drew in the area of aquarium and did not write any comment. One pair of pupils put all the types of candies on the bottom, one of each kind, so it is not possible to compare the solution with the pupils of grade 2. Two pairs of pupils drew the candies before and after putting them into the water. The candies in water are smudged (see Figure 10).

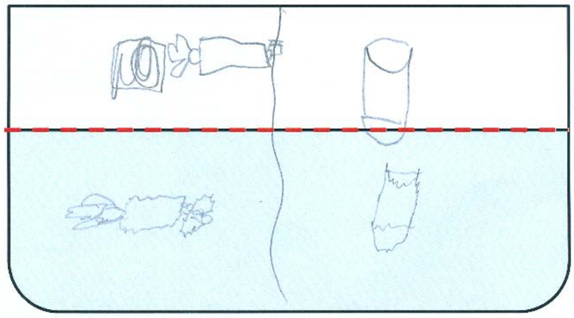

Figure 10. Solution trying to respect the optics of the water

In this paper we wanted to demonstrate the importance of informed choice of the problems for the classroom. When the task has “low floor and high ceiling” [24] it has the potential to be tailored according to pupils’ needs and potential by an experienced teacher. We tried to provide the reader with three different orchestrations of the same investigation, and point out the different knowledge and experience that could be obtained by the involved pupils.

Surprisingly, the usual misconceptions about the density [19] that sinking or floating depends on the mass of the investigated object were not manifested. On the other hand, we found out that the second-graders and substantial portion of fourth-graders shown the inability to predict the behaviour of the objects in a wider vessel. In our data the decrease of this misconception can be observed, even though it is not possible to evaluate the difference between grade 2 and grade 4 statistically as the participating pupils were not picked randomly and the effects of age and schooling cannot be separated.

During the science investigation we tried to improve the statistical literacy of participating pupils. However, lots of pupils recorded their measurements of volume, but none of them calculated the result. They were able to compare the density without estimating its value. This fact may be a result of stronger teacher's focus on the concept of density than on statistical literacy.

4. Conclusions

Different knowledge can be obtained by pupils with different background. While pre-school children gain the first experience with systematic scientific approach, second-graders were provided by an opportunity to measure the volume and mass. The fourth-graders even started their own statistical investigation, as some of them did their first, naive reasoning according to the obtained data.

The final whole-class discussion showed to be a crucial part of the lesson, as in the case of grade 2 pupils only during this part of the lesson the pupils got the correct answers to the task and got the opportunity to formulate and classify their findings into the form of a new piece of knowledge.

It is a pity that the session in the kindergarten preceded the primary-school sessions, as we were not able to investigate the children predictions about the behaviour of the objects in the wider vessel, the aquarium.

Further investigation is necessary to deeper understand the children's and primary-school pupils' conceptions about water, as our results indicate that children at this age are not able to foresee how different objects would behave in this environment. Also, investigating the relation with pupils' level of experience with e.g. swimming can shed more light on this interesting issue.

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