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Practical School Experiments with the Centre of Mass of Bodies

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The concept of the centre of mass of a rigid body as a virtual point where the weight force acts is not easy to understand without a number of supporting school experiments. In school practice, however, experiments on this topic are often limited to a few of the simplest cases in which a simple flat body, such as a triangle or rectangle, is hung in two or mostly three directions to show where the corresponding plumb lines intersect. Typically, simple wooden bodies are used, on which the plumb lines are already drawn through the centre of mass. However, such experiments can be boring for students and are probably insufficient to illuminate all aspects of the topic. Furthermore, if the experiments are only demonstrated by the teacher rather than being performed in groups, the opportunity to train students' skills and develop nature-science competences is missed. We therefore prepared and performed a series of group experiments in logical sequence for students of the 8th and 9th grades of primary school, so that their full active participation was invoked. The experience with such an experiment setup with very simple equipment, together with the open discussion of results, increased pupil motivation for physics and perhaps also improved understanding of some physics problems regarding the centre of mass, even for younger students.

Keywords: centre of mass, practical school experiment, nature-science competences

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Priročni šolski poskusi s težiščem teles

Robert Repnik in Milan Ambrožič

Koncepta težišča trdnega telesa kot navidezne točke, v kateri je prijemališče teže, ni lahko razumeti brez večjega števila podpornih šolskih poskusov. Poskusi na to temo so v šolski praksi pogosto omejeni na nekaj najpreprostejših primerov s ploskimi telesi, kot sta trikotnik in pravokotnik, ki jih obesimo v dveh ali največ treh smereh, da bi poiskali točko, v kateri se sekajo težiščnice. Navadno se uporabi nekaj lesenih teles, na katerih so težiščnice že narisane, vendar pa utegnejo biti takšni poskusi za učence dolgočasni, poleg tega pa verjetno ne zadostujejo za osvetlitev vseh vidikov težišča. Če so poleg tega poskusi izključno demonstracijski, namesto da bi jih izvajali učenci sami po skupinah, učenci s tem izgubijo priložnost razvijanja spretnosti in naravoslovnih kompetenc. Zato smo pripravili in v šoli izvedli vrsto skupinskih poskusov za učence osmega in devetega razreda osnovne šole, pri čemer so bili učenci polno aktivni. Izkušnje s takšno postavitvijo poskusov in z odprto diskusijo rezultatov so pokazale povečano motivacijo učencev za fiziko in mogoče tudi boljše razumevanje nekaterih fizikalnih problemov v povezavi s težiščem, celo pri mlajših učencih.

Ključne besede: težišče, priročni šolski poskus, naravoslovne kompetence

Introduction

According to the national curriculum of Slovenia, the centre of mass is a topic that is taught within the subject of forces in the 8th grade of primary school (students aged 13 or 14), and later briefly in secondary school within the subject of forces and torques (students aged 15 or 16). In primary school, the level of understanding and the skill of determining the position of the centre of mass is limited to geometrical and non-geometrical bodies in two dimensions (2D). Subsequently, in secondary school, nothing essentially new is added to the topic of the centre of mass.

Acquiring the concept of the centre of mass in more detailed objects, particularly in real three-dimensional (3D) ones, is crucial for understanding several phenomena in nature and everyday life, such as: 1) stable and labile static equilibrium, 2) oscillation of a physical pendulum and its oscillation time, 3) rotation of rigid bodies in general, 4) complex movements of rigid objects composed of translational and rotational motion, etc. Of course, there are also practical applications of the understanding these phenomena; for example, in the case of the equilibrium of floating objects, such as ships.

In the authors' opinion, the usual experimental verification of the centre of mass of some simple flat bodies (mostly triangles, rectangles or trapezes) by hanging them on a string can be rather boring for students, particularly when only a few demonstration experiments are done by the teacher. This does not seem to develop the natural science competences of students very much. Several quite interesting experiments with 3D bodies (from simple bodies, such as a cube or tetrahedron, to more sophisticated shapes, achieved by merely combining and sticking together simpler objects) can be added to make the topic more attractive. Even using some other 2D objects can add sufficient interest; for example, a circular ring or an ellipse. In addition, such experiments can be done alone by students organised into groups. In this way, various other skills can be trained simultaneously, such as motoric and mathematical skills, not to mention the competences of interpersonal interaction, etc.

Our experiments support the inquiry-based activities that are desired and required in teaching nature-science subjects (DeBoer, 1991; Jones, MacArthur, & Akaygün, 2011). In connection with these requirements, the problem may arise that preservice teachers themselves have too little personal experience with the concepts of scientific work (Gabel, 2003; Newman, Abell, Hubbard, McDonald, & Martini, 2004). Inquiry-based education with the active participation of students has a positive effect both on acquiring a proper understanding of the scientific topic in question and on learning inquiry skills (Flick

& Lederman, 2006; Minner, Levy, & Century, 2010). This holds for students as well as for teachers. According to Šimenc, however, a great deal of time and effort is needed for the teacher to build his or her own inquiry skills and to apply them at school (Šimenc, 2008). Thus, meetings of the teacher and students with an active researcher with fresh ideas about any school topic can be extremely useful. Systematic research has indubitably shown a strong connection between the teacher's knowledge, scientific skills and the corresponding self-confidence in teaching science, on the one hand, and an increase in student motivation for science, on the other (Jarvis, Pell, & Hingley, 2011). Furthermore, inquiry-based learning can incorporate different learning styles according to the VARK model, i.e., visual, aural, read/write and kinesthetic/tactile (Fleming, 1995; Oblinger & Oblinger, 2005).

Group experimental work guided by the teacher, where the students try to solve specific experimental tasks alone and then verify and discuss the results in groups, can be attributed to the constructivist approach in teaching physics (Kariž Merhar, 2008; Kline, 2010; Marentič Požarnik, 2004; Potočnik, 2004; Plut Pregelj, 2008). In the work of Kline, the success of the constructivist approach was compared (using tests of knowledge) with the traditional approach with some constructivist elements in the case of two physics topics in the 8th grade: pressure and buoyancy. It is interesting to note the findings: while there were no statistically significant differences in the success of both approaches in the case of the more elementary topic of pressure, the constructivist approach was proven to be more successful in the case of the more demanding topic of buoyancy. Other didactic research activities in Slovenia confirm the finding that the constructivist approach is particularly advantageous when the physics topic being taught is a synthesis of lower-level topics (Kariž Merhar, 2008).

Science education and systematic motivation for science before the age of 14 is highly recommended in order to meet the need for scientists and technologists in the European society of knowledge (Osborne & Dillon, 2008; Pell & Jarvis, 2001). Furthermore, according to a UNESCO investigation (UNESCO, 1991), even young children seek to understand the fundamentals of the world; of course, often differently from the way the teacher presents such knowledge in school. Nevertheless, children's ideas might be of some use, and the teacher or expert should help them to find common meaning.

Thus, we prepared and performed a series of logically sequenced group experiments for primary school students. Our aim was to study the effects of these experiments on students' motivation and on their understanding of the concept of the centre of mass.

Research problem

Our aim was to determine how the implementation of a set of various experiments from the topic of the centre of mass, prepared for group work in school, influences:

1. student motivation,
2. acquiring a true understanding of the concept of the centre of mass.

In addition to the qualitative observations of the teacher or other performer of the physics workshop, a corresponding pre-test and post-test were also used in the study.

Methods

We first describe the experiments and their method of realisation. In some cases, but not all, we also performed some motivational frontal experiments. Due to the limited space in the present article, we will describe only the typical group experiments.

The experiments for determining the centre of mass can be divided into two types: 1) hanging a body on a string, and 2) pushing a body over the edge of a table. For the sake of brevity, we will call them "hanging" and "pushing" experiments, respectively. It is suggested to combine both types of experiments for all testing bodies, with an emphasis on pushing experiments. The bodies (objects) may be (approximately) two-dimensional (2D) bodies (such as a rectangle or triangle cut from paper), bodies made of thin sticks, three-dimensional (3D) bodies with the mass concentrated on the surface, etc.

The experimental requisites for the students' group experiments are: firm paper, scissors, pencils, pairs of compasses, rulers, a paper punch, thread or string, different weights, sticks, stands for hanging experiments, plasticine for connecting parts of objects, sticking tape, elastic bands (loops), spring balances, and paper clips for making small hooks.

The number of students in each group, sitting at the same desk with one experimental setup, was three or four. The students in each group were encouraged to divide their work at their discretion. Typical group experiments (among many other possible examples) are the following:

Experiment 1

The group performs an experiment with one of the wooden plates that have pre-drawn plumb lines through the centre of mass. They first push the object over the table slowly, with one of the drawn lines parallel to the edge of the table (pushing experiment). They check whether the object falls when the plumb line with the centre of mass is aligned with the table edge. They may also check other directions, not drawn. This is a good opportunity to check the accuracy and precision of the students' work. Next, they hang the same object on a stand with a string (hanging experiment). They check whether all of the plumb lines are aligned with the string in the vertical direction.

Experiment 2

The group performs an experiment similar to the previous one using a ruler with a millimetre scale. The ruler is just a substitute for a rectangle. The motivation for this experiment is that the students guess and verify whether the ruler is a rectangle as an approximate 2D geometrical object.

Experiment 3

The group cuts different 2D objects out of cardboard or firm paper (hereinafter referred to merely as "paper"). The objects can be more or less symmetrical: triangle, rectangle, circle, circular ring, etc. (Figs. 1 and 2). The students again perform both types of experiments to determine the centre of mass. This time, they use pencils and rulers in the pushing experiments to draw the corresponding plumb lines. For the subsequent hanging experiments, some small holes should be made near the edges of the paper objects using a paper punch. In addition, the students can do similar experiments with an object with no symmetry at all. For instance, we prepared the outlines of maps of Slovenia and Croatia, with a size of approximately 15 cm in one of the directions. The maps were obtained from the Internet, printed on normal paper, stuck onto firm paper and then carefully cut out. This may also be a useful exercise for student homework.

Figure 1. Some pushing experiments involving determining the plumb lines of cardboard objects.

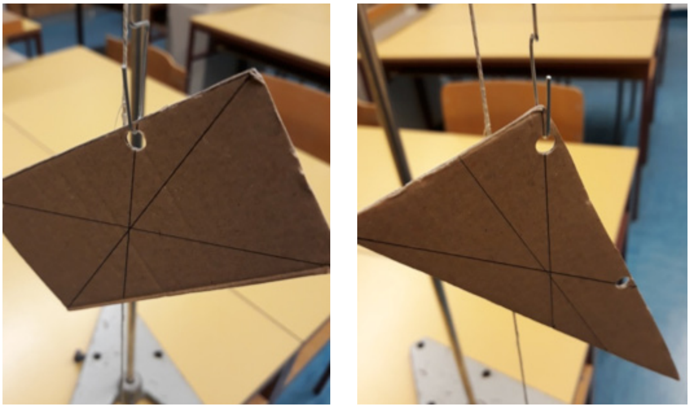

Figure 2. Some hanging experiments using the same objects as in the pushing experiments. In this case, the string was not completely stretched because the paper objects were not heavy enough relative to the hanging string; therefore, a parallel string with a heavier hanging object (e.g., a ruler) was used so that the student could compare the true vertical alignment of the plumb lines.

Experiment 4

Students can execute a pushing experiment with a ruler and a weight with a comparable mass. Since the weight has a known mass, the students use a spring balance (newton meter) to measure only the unknown mass of the ruler. They place the weight on the ruler at one of the ends, and then execute a pushing experiment (Figure 3). They can try two variants: the weight can be positioned at the end of the ruler that rests on the table, or it can be positioned at the end that extends beyond the table. The students are encouraged to note down the data and, by themselves as homework, try to find a quantitative relation between the lengths and masses.

Figure 3. A pushing experiment with a ruler and a small weight (left), and with a tetrahedron cut from paper (right). In the experiment on the left, the ruler was slowly pushed along its length over the edge of the table, so that the weight on the ruler was increasingly near the edge.

Experiment 5

The paper can also be used to make the faces of different geometrical bodies, such as a cube or a regular tetrahedron (Figure 3, right). It is a good exercise for the students to determine (or remember) how to make such a connected surface skeleton from just one piece of paper. After the skeleton is cut out, the side faces can be stuck together using sticking tape, with their edges together. Since it is difficult to determine the centre of mass of 3D bodies in a practical way, the pushing and hanging experiments are done only to get a qualitative feeling of the position of the centre of mass, and perhaps to guess its exact location.

Experiment 6

Skeletons of 3D geometrical bodies, such as cube or tetrahedron, can also be made with the use of sticks fastened together with plasticine or similar. However, the students should be aware (the teacher must pay particular attention to this fact) that the distribution of mass is very different in the case of "full" bodies, their surface skeletons (as in the previous paragraph), and their edge skeletons (as in this paragraph).

Experiment 7

This experiment was performed qualitatively or quantitatively. A ruler (or perhaps two rulers fastened together with an elastic band to double the length) is hung on a stand. This could be done easily, because our rulers had small holes near one end. The ruler was moved slightly from equilibrium and allowed to oscillate. The oscillation time was measured with a wristwatch or smartphone, or just roughly estimated.

Methods

The effect of the proposed experiments on the students' critical reasoning, as well as on their attitude to science, is evaluated by different means, depending on the circumstances. The cooperation and motivation of students during experiments is valuable information, but only on a qualitative basis. For a more quantitative evaluation of the success of our didactic strategy, we use a corresponding pre-test and post-test, which are presented in the Appendix.

Sample

Four different research samples were studied in 2017, all involving different ages, event occasions, workshop durations and test examinations: 1) at the end of May, at the final gathering that concluded the lecturing year for young students (Mini University of the Faculty of Arts – MUF) held at the Faculty of Arts, University of Maribor; 2) at the beginning of June, at a study camp for gifted pupils at the Paški Kozjak Primary School; 3) and 4) in September, in regular 9th grade classes at two primary schools (denoted simply S1 and S2) in two different regions of Slovenia. The numbers of the experiments listed above (performed either partially or entirely) will be given separately for each sample.

MUF (Mini University of the Faculty of Arts)

The MUF is a "university for children", where scientists from different faculties of the University of Maribor try to encourage the interest of primary school students in science and scientific questions, including the area of natural sciences, among them physics. The teaching level and language is adapted to the age of the participants. The main audience in the concluding gathering of the MUF was pupils from the 4th to the 8th grade, as well as their parents. All of the experiments were frontal, and there was no pre-test or post-test. Performed experiments: 1, 2, 4 and 7.

Paški Kozjak

Four primary schools from Slovenian Carinthia have established a traditional annual meeting towards the end of the school year. It is a two-day camp for gifted students from the 6th to the 9th grade, with a workshop on various subjects running simultaneously. This year, eight students chose the physics workshop, which lasted about three school periods (three times 45 minutes or slightly longer). The students were divided into two groups of four, each with the same experimental equipment (Figure 4). There was no pre-test or post-test, just short open discussions of the results of the experiments. Here, the constructivist approach was adopted in full, as enough time was available. Performed experiments: all experiments from 1 to 7.

Figure 4. Group experiments about the centre of mass at Paški Kozjak.

Primary school S1

The workshop was executed with two 9th grade classes in a row (a total of 17 students, with both valid tests given). For each class, the workshop lasted 45 minutes, as it was performed as a regular physics lesson. The students were divided into groups of three or four, each with the same experimental equipment. The pre-test and post-test were given (each lasting five minutes), so there was only 35 minutes remaining for experiments. Performed experiments: from 2 to 5.

Primary school S2

The workshop was executed with three 9th grade classes in a row (a total of 51 students, with both valid tests given), and the workshop lasted 75 minutes for each class. The group work and the experimental setup and equipment were similar to those used in sample S1. The physics workshop was part of a technical day with two other simultaneous workshops (so the three classes rotated in three workshops). A short description of the workshops with some photographs is available on the school web page (Solkan Primary School, 2017) listed in the references below. As in the case of S1, the pre-test and post-test were given (each lasting five minutes), so there were still 65 minutes available for experiments. Based on the authors' previous experience (difficulties encountered by students of S1 in answering some questions) the post-test was modified slightly for S2. Performed experiments: from 1 to 6.

Results and interpretation

Due to the different workshop conditions for the different sample groups, the results are given separately.

MUF

One of the authors presented a short simplified talk (roughly 15 minutes) about the centre of mass, together with demonstration experiments. Of course, the time was too short and the students too young to perform all of the experiments described above, but some other suitable experiments were executed. The author invited four students to cooperate in the experiments. The experiments demonstrated included hanging experiments with maps of Slovenia and Croatia, a pushing experiment with a ruler, the oscillation of the ruler or two connected rulers as a physical pendulum, etc. According to the author's experience and the feedback after the demonstration, all of the children as well as their parents in the audience were quite interested in the experiments.

Paški Kozjak

Based on the observations of the author, we mention the following. The experiments were executed with no special difficulties. There was enough time for all of the experiments listed above. The students were interested in the experiments and showed a good level of manual skills; for example, they quickly determined how to construct the surface skeleton for the tetrahedron, once the author had shown them how to construct the simplest body, the equilateral triangle. A few of the students demonstrated good physics intuition regarding topics not even taught in primary school physics.

Primary school S1

Many of the students forgot to identify themselves with the same code on both tests (or were not focused enough to solve the post-test), which is why there were only 17 valid pairs of pre-test and post-test results. The experiments involving determining the centre of mass both by pushing and hanging were executed on the following objects cut from paper: rectangle, triangle, circle, circular ring, cube and tetrahedron surface. Based on the author's experience, 35 minutes (including the time required for the students to sit down and receive some formal information from the teacher) is far too short a time to perform the series of the experiments carefully. There was no frontal explanation of the results of experiments, just casual comments between the experiments (the same was true for sample S2 below). The results of the tests are shown in Tables 1 to 3.

Primary school S2

All of the students identified themselves correctly with the same code on both tests, as there was no hurry to finish the lesson and go to the next classes, as was the case at school S1. Based on the author's experience, 65 minutes is just adequate to perform the series of experiments with adequate descriptions.

The results of the tests are shown in Tables 1 to 3 and in Figure 5. The following symbols will be used in the discussion below: $P_{\mathrm{I}i}$ (initial points, i = 1 to 5) is the number of points achieved in the i-th question and for the individual student in the pre-test; $P_{\mathrm{F}i}$ (final points, i = 1 to 5) is the corresponding result in the post-test; and $D_i = P_{\mathrm{F}i} - P_{\mathrm{I}i}$ is the corresponding difference between the tests (see Figure 5).

Table 1

The mean number of points per question for each school separately

Question	Max. points	S1 (17 valid pairs)		S2 (51 valid pairs)	
		Pre-test	Post-test	Pre-test	Post-test
Q1	1	.18	.29	.69	.69
Q2	2	.88	-.18	.96	1.08
Q3	1	-.65	-.35	.00	.49
Q4	2	1.06	1.24	1.43	1.37
Q5	1	.65	-.53	.37	.39

Note. $<P_{Ii}>$ for the pre-test and $<P_{Fi}>$ for the pre-test. For instance, $<P_{I1}>$ = .18 and $<P_{F1}>$ = .29 for S1, etc. The second column shows the maximum number of possible points for each question = the number of correct answers shown in the Appendix.

Table 1 shows the average number of points achieved for two samples, for both tests and for each question separately. A negative mean result means that more than half of the students gave the wrong answer (in the case of only one answer chosen). Therefore, a zero mean value denotes the success of half of the sample in answering the question (see the explanation for evaluating the tests in the Appendix). Except for the last question, the results of the pre-test are better for sample S2 than S1. It is somewhat surprising that the results in questions Q2 and Q5 of the post-test for sample S1 are so much worse than in the pre-test. Perhaps the students were slightly confused at the end of the lesson due to the hurry and the number of experiments. The students from school S2 obviously obtained better average results in all of the post-test questions than those from S1, particularly in Q2 and Q5. The two most probable reasons for this are: 1) the students of S2 had more time and were in less of a hurry, 2) the post-test questions for S2 were changed due to the poor results of S1 students, and therefore probably easier (the differences are mentioned in Appendix A).

SPSS software was used to reveal some differences on a solid statistical basis. The Mann-Whitney *U* test was used, which works well for non-Gaussian distribution and for very different sizes of compared samples (in our case 17 and 51). In the first statistical test, the differences D_i were compared for both schools and for each question. The test revealed significant differences between S1 and S2 only for questions Q2 and Q5 (as expected from Table 1): for Q2 U = 263.5 with P = 0.002 (2-tailed asymp.sig.), while for Q5 U = 255.0 with P = 0.005 holds. For the other three questions, the differences D_1, D_3 and D_4 were not significant for S1 and S2; it is true that the results of the post-test were better in the case of S2, but so were the results of the pre-test. In the second Mann-Whitney *U* test, only questions Q2 and Q5 were treated, but separately for the pre-test and the post-test. Again, differences in results for both schools were analysed. The entire table (Tables 2 and 3), obtained from SPSS is given below.

Table 2
Mann-Whitney U test – ranks (SPSS)

Query	School	*N*	Mean rank	Sum of ranks
Q2 pre-test	S1	17	34.50	586.50
	S2	51	34.50	1759.50
	Total	68		
Q2 post-test	S1	17	**21.26**	361.50
	S2	51	**38.91**	1984.50
	Total	68		
Q5 pre-test	S1	17	38.32	651.50
	S2	51	33.23	1694.50
	Total	68		
Q5 post-test	S1	17	**25.53**	434.00
	S2	51	**37.49**	1912.00
	Total	68		

Table 3
Mann-Whitney U test – statistics (SPSS)

	Q2 pre-test	Q2 post-test	Q5 pre-test	Q5 post-test
Mann-Wh. *U*	433.5	**208.5**	368.5	**281.0**
Wilcoxon W	586.5	361.5	1694.5	434.0
Z	.000	-4.293	-1.160	-2.499
Asymp. sig.	1.000	**.000**	.246	**.012**

While there were no statistically significant differences between both schools in solving pre-test questions Q2 and Q5, the corresponding post-test questions were answered significantly better by the students of S2 (bold numbers in Tables 2 and 3; see also Table 1 for averages). Therefore, the post-test was the main contribution to test differences D_2 and D_5. The most probable explanation for this difference is that the students from S1 had too little time available, as mentioned above. But why just questions Q2 and Q5? Because they seem to be slightly more difficult than the other questions. Finally, we should mention the results regarding Q3. It is surprising that such a difference between the schools in the pre-test is evident in Table 1. Among the incorrect answers to this question, the answer that the mountain has its centre of mass at half-height was chosen most often (see Appendix).

Since there were 51 students with valid pre-tests and post-tests in sample S2, we can also present the results for individual students and for each question separately as the difference D_i between the points achieved in the post-test and the pre-test. The corresponding histograms for questions Q2 and Q5 are shown in Figure 5. The histograms were verified for other questions, as well, but no particular differences were determined. It should come as no surprise that the presented histograms are not very similar to Gaussian histograms; firstly, the sample is small, and secondly, the differences D_i can only have a few integral values.

Figure 5 shows that most of the students received the same number of points for each question in the post-test and the pre-test (D_i = 0). The same holds for the other three questions. This is in accordance with small differences of mean values for both tests in Table 1. This does not mean that experimental group work of this kind is inefficient; we must bear in mind that the students had already attended lectures about the centre of mass in 8th grade physics. Furthermore, in the authors' opinion, the post-test should be done later, in a separate physics lecture, if possible. Most probably, the impressions about the experiments take time to settle in the students' memory, and some additional explanation from the teacher would also be useful. We have recommended this to current physics teachers, in case they intend to repeat similar experiments themselves.

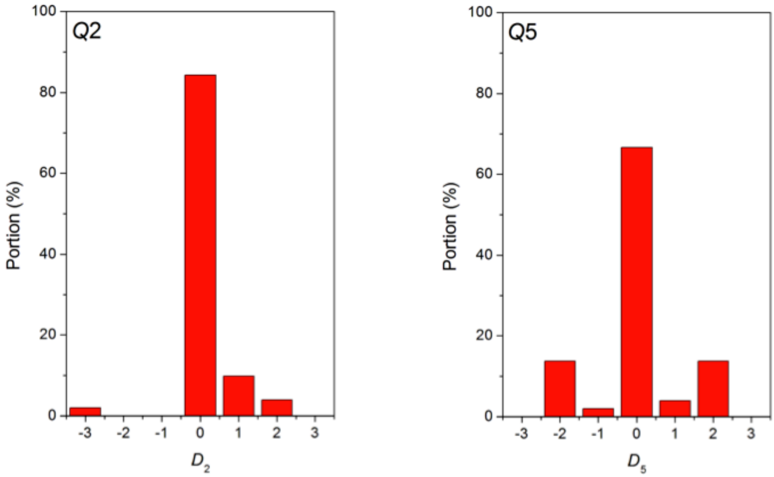

Figure 5. The histograms of the test differences D_2 and D_5 for individual students in sample S2. The vertical axis corresponds to the portion of students as percentages.

Among additional qualitative observations, with regard to the 9th grade primary school samples, it was observed that some aspects of geometrical knowledge and skills, e.g., about using the pair of compasses to draw a regular triangle, had been forgotten. Therefore, such experiments are also valuable for maintaining various mathematical skills. Ambrus discusses various aspects of the relationship between the mechanisms of mind and more successful teaching/learning of mathematics (Ambrus, 2014). Among the interesting points in his article relevant to our work, we mention the following:

1. The mind uses metaphors to facilitate memorising, and abstract ideas are represented by concrete examples.
2. Besides audial and visual information channels, we should also use the motoric/tactile memory, which is very accurate: about 90% of the content of what is done or spoken aloud is remembered.
3. Closed problems should sometimes be transformed into open ones.

This is exactly what was done to relate at least some of the physics experiments regarding the centre of mass with geometry in a mathematical sense.

We should also stress the most crucial difference between the experiments denoted by numbers 1 and 3 above: while the plumb lines are already drawn in experiment 1, the students draw the plumb lines themselves in experiment 3. We suggest that if teachers do not have enough time to execute all of the above experiments in school, they should choose the group experiments in which the students determine and draw the plumb lines themselves (perhaps on pre-prepared plastic objects from which pencil lines can be easily erased after the lecture). This is more fun and better for the development of the students' competences than just verifying pre-drawn plumb lines.

Conclusions

According to our experience, the implementation of the group experiments described regarding the centre of mass demonstrated that the motivation was very high for all of the research samples listed above. Although it is impossible to measure the development of different skills in such a short period, it was observed that the motor skills of individuals in the groups were satisfactory. Geometrical reasoning was also good, although a few details from lower grade lectures had been forgotten.

For a more systematic investigation of the success of the experiments discussed above, we suggest that, over a period of at least a few years, the tests should be undertaken in the 8th grade, when the centre of mass is treated in physics lessons. We recommend reserving two lessons for this topic. These do not necessarily have to be physics lessons; physics can be combined with mathematics or technical studies. This can be arranged simply if the same teacher teaches both physics and mathematics, for instance; otherwise, two teachers should cooperate. If the teacher repeats this series of experiments a few years in a row and compares the qualitative observations with control groups (i.e., a class where something else is done in connection with this physics topic), he or she should be able to determine the usefulness of the proposed experiments.

Several modifications of the described group experiments can be made; for example, a smartphone camera could be used in the pushing experiments with objects cut out of paper, and the plumb lines could thus be determined on photographs. It would be interesting to compare the measurement accuracy if different student groups used different experimental approaches. The teacher could decide to prepare paper skeletons of some 3D objects alone prior to the lesson. It might also be a good exercise for students to discuss the sources of the measurement/preparation error of such objects as compared to ideal geometrical objects (the effect of glue, sticking tape, etc.).

Appendix: Pre-test and post-test

More than one correct answer is possible for some questions, and the students were warned about this. Correct answers in the tests below are marked with a plus sign (+). In aggregating the points, each wrong answer chosen results in one negative point, while each correct answer chosen results in one positive point. The students were intentionally not informed about this evaluation system. Below, we present the pre-test (the same for S1 and S2) and the post-test for S2 only.

The questions in the pre-test were as follows:

1. Where is the centre of mass of a human being?
   a. In the head.
   b. In the chest.
   c. In the stomach. +
   d. Between both knees.
   e. In both feet.
2. Where is the centre of mass of a rectangle?
   a. Halfway along the longer side.
   b. Halfway along the shorter side.
   c. At one of its vertices.
   d. At the intersection of its diagonals. +
   e. At the intersection of the symmetry axes of the sides. +
3. Where approximately is the centre of mass of a mountain?
   a. At its top.
   b. At its bottom at ground level.
   c. At half height.
   d. Below half height. +
   e. Above half height.
4. Which claims are true?
   a. If more than half of the length of a ruler is pushed over the edge of a desk, the ruler stays on the desk (the ruler is perpendicular to the edge).
   b. When a ruler is pushed over the edge of a desk, the ruler stays on the desk when more than half of its length rests on the desk (the ruler is perpendicular to the edge). +
   c. A book stays on the desk when it is pushed over the edge, but the side diagonal that is parallel to the edge remains on the desk. +
5. When a concentric circle with a smaller radius is cut out of a full circle made of paper, what happens to the position of the centre of mass?

a. The centre of mass disappears, since the centre of the ring is in the hole.
b. The centre of mass is still in the geometrical centre. +
c. The centre of mass moves so that it is somewhere in the body of the ring.

The questions in the post-test were as follows:

1. Where is the centre of mass of a human?
a. In the brain.
b. In the lungs.
c. Under stomach and liver. +
d. Between both knees.
e. In both feet.
2. Where is the centre of mass of a rectangle?
a. Halfway along the longer side.
b. Halfway along the shorter side.
c. At one of its vertices.
d. At the intersection of its diagonals. +
e. At the intersection of the symmetry axes of the sides. +
3. Where approximately is the centre of mass of a pyramid (with the base on the ground)?
a. At its top.
b. At its bottom at ground level.
c. At half height.
d. Below half height. +
e. Above half height.
4. Which claims are true?
a. If more than half the length of a ruler is pushed over the edge of a desk, the ruler stays on the desk (the ruler is perpendicular to the edge).
b. When a ruler is pushed over the edge of a desk, the ruler stays on the desk when more than half of its length rests on the desk (the ruler is perpendicular to the edge). +
c. A book stays on a desk when it is pushed over the edge, but the side diagonal that is parallel to the edge remains on the desk. +
5. From a square made of paper, we cut a smaller square with parallel sides so that their centres coincide. Where is the centre of mass of the figure/frame?
a. The figure does not have a centre of mass, since it should be in the hole.
b. In the common centre of both squares. +
c. Outside the square hole, but inside the figure.

We should mention that some of the post-test questions for sample S1 obviously proved to be more difficult than assumed. For instance, Q1 was expressed in height for a man with the height of 180 cm. Q5 supposed a sphere with a cut-out smaller sphere instead of a square. The results of the students from S1 in answering this question were much worse than the corresponding question in the pre-test. It seems that, in this case, transforming the problem from 2D to 3D requires a significant mental leap.

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