Results of Czech gymnasium students in the TIMSS Advanced 1995 specialized physics test repeated in 2023

Petra Pschotnerová[1,*], Dana Mandíková[1], Martin Chvál[1]

[1] Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Prague, Czech Republic; petra.pschotnerova@matfyz.cuni.cz

The paper presents the first results of the TIMSS Advanced 1995 specialized physics test re-administered to final-year students of gymnasiums in the Czech Republic in 2023. In 2023, we used the original test booklets from 1995 in paper form. Of 90 gymnasiums from 1995, 72 participated in the repeated survey. Another 10 gymnasiums participated as replacement schools. In 1995, 819 students participated in the physics test. In the paper, we work with a sample of 1602 students from 2023. The overall mean achievement of students has decreased significantly compared to 1995. Males worsened more than females. Student mean achievement significantly lowered in all five physics content areas. The largest decrease in mean was observed in items from mechanics. More than a 10% decrease in the mean achievement most often appeared in items from the area of modern physics. In the case of open-ended items to which students had to create their own answers, the decrease in mean achievement was mainly due to the fact that students did not solve them at all. This may be due to the lower knowledge of the students caused by the reduction in the number of lessons devoted to teaching physics, but also to the lower motivation of the students when solving the test.

Key words:
TIMSS Advanced 1995, physics test, Czech gymnasium students.

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1 Introduction

International study assessments can serve as an objective tool for comparing the level of mathematical, reading, and science literacy of students. Namely, the TIMSS (Trends in International Mathematics and Science Study) and PISA (Programme for International Mathematics and Science Study), whose established methodology and regular cycle of their implementation make it possible to monitor trends in the learning outcomes of students in the participating countries.

The Czech Republic has been participating in the international surveys TIMSS and PISA since their inception, in the case of TIMSS since 1995 and in the case of PISA since 2000. However, this does not apply to all populations of tested students and all parts of these studies. One of the exceptions is, for example, the TIMSS Advanced study, in which the Czech Republic participated in 1995 for the first and last time. The TIMSS Advanced international assessment was also held in 2008 and 2015.

TIMSS Advanced measures the learning outcomes of students in the final year of secondary school enrolled in special advanced mathematics programs and physics programs (or tracks). In the Czech Republic, in 1995, this group was represented by students in the final year of general secondary schools (gymnasiums[1]).

The reason why we focused specifically on TIMSS Advanced is that in 1995 a representative sample of upper secondary school students whose curriculum included physics was tested in the Czech Republic. Today, the situation with compulsory teaching of physics in secondary schools is the same, because physics education is especially included in the educational programmes for gymnasiums (Pschotnerová, 2021).

In 2021 we conducted a questionnaire survey among physics teachers and final-year students who chose to take the final examination in physics. The results of the survey showed that the final examination in physics at the end of upper secondary school studies differs to a certain extent between schools and cannot serve as an objective tool to measure the results of physics education (Pschotnerová & Mandíková, 2024). In addition, only about a tenth of final-year students choose the final examination in physics.

All these findings supported our decision to repeat the TIMSS Advanced specialized physics test from 1995 among students in the final year of gymnasiums in the Czech Republic. In this paper, we discuss the methodology and results of the current testing, as well as the comparison of the results with the results from 1995.

It is also important to point out that since 1995, the Czech education system has not undergone a more fundamental reform in the field of secondary school physics education.

[1]The term gymnasium will refer to a general secondary school.

2 Theoretical framework

2.1 International surveys in the Czech Republic

International comparative studies such as PISA or TIMSS conducted in the Czech Republic focus especially on pupils of primary and lower secondary schools.[2] A basic overview of international studies carried out in the Czech Republic is given by Potužníková et al. (2014).

TIMSS and PISA measure, among others, science literacy that includes physics. Neither of them deals exclusively with students' knowledge and applications of physics concepts. An exception to these surveys was the TIMSS Advanced specialized physics test conducted in 1995, 2008 and 2015.

It is worth noting that since 1995, the mean achievement of fourth- and eighth-graders in science has been significantly higher than the TIMSS international average. The results of Czech eighth-graders in physics test items deteriorated significantly between the years 1995 and 1999, however, they improved slightly by 2007 (Mandíková et al., 2011). In 1995, the achievement of Czech upper secondary school students in science literacy was comparable to the international average achievement, but in the TIMSS Advanced physics test they had significantly lower mean achievement (Mandíková, 2022). You can find more information on the results of Czech students in recent cycles of the TIMSS survey in the TIMSS national reports (Tomášek et al., 2008; Tomášek et al., 2012; Tomášek et al., 2016; Tomášek et al., 2020).

2.2 Tested students and sample construction in TIMSS 1995

In the TIMSS 1995 study, three populations of students were tested (Martin & Kelly, 1996):

1. Population 1: students enrolled in the two adjacent grades that contain the largest proportion of students of age 9 years at the time of testing (mostly students in the third and fourth grades);
2. Population 2: students enrolled in the two adjacent grades that contain the largest proportion of students of age 13 years at the time of testing (mostly seventh and eighth graders);
3. Population 3: students in their final year of secondary education (including students in vocational education programs).

   Within Population 3, the participating countries had the opportunity to test two subgroups of students:

   a) Students who have studied advanced mathematics.

   b) Students who have studied physics.

For each country, a necessary condition for participation in the study was to test students of Population 2, the other populations, and parts of the survey were optional. Our study focuses on a subgroup of students in Population 3 who have studied physics in upper secondary school.

The sampling design was a process that took place in two stages. In the first stage, a school was sampled with probability proportional-to-size, in the second stage, a fixed number of students, most often the entire class of students, was sampled (Martin & Kelly, 1998).

2.3 Design and types of test items in the TIMSS 1995 survey

The development of the TIMSS achievement test items followed analyses of the curricula of participating countries. Curriculum frameworks describe the subject-matter content and performance expectation elicited by the test items in the TIMSS achievement tests. The three main dimensions of the TIMSS science curriculum framework (subject-matter content, performance expectation, and perspectives) can be found in Chapter 1.3 of the TIMSS technical report (Martin & Kelly, 1996). For complete TIMSS curriculum frameworks, see the publication written by Robitaille (1993).

In order to cover the largest possible scope of the curriculum, the TIMSS tests used a cluster-based design. Individual test items were divided into a set of mutually exclusive groups, the so-called clusters. The number of items in the clusters varied because an estimated number of minutes that a typical student would need to solve the items in the cluster was defined for each cluster. Then, the clusters of items were systematically divided into test booklets. One cluster could appear in only one test, but also in several test booklets (tests). Each student was assigned one test booklet (Martin & Kelly, 1996).

TIMSS tests consisted of multiple-choice items with one correct answer at a time. The tests also contained open-ended items of two types: items with a short-answer and extended-response items. Open-ended items were coded using a two-digit coding scheme. The first digit of the code indicated the level of correctness of the answer, and the second digit represented the type of answer. Using the frequencies of

[2] In the case of PISA, students of the first years of upper secondary schools are also tested.

codes for selected open-ended items, for example, typical students' misconceptions when solving physics items can be identified, see Angell et al. (2000). Such analyses support the strength of the TIMSS framework design.

2.4 The international context of the TIMSS Advanced study

The educational systems of participating countries differ to a large extent. It is particularly complicated for countries to select a sample of students representing Population 3. Also, for this reason, a large part of the countries has given up to repeatedly participate in the TIMSS Advanced study. Descriptions of educational systems and definitions of Population 3 of the TIMSS Advanced 1995 participants provide Mullis et al. in Appendix A (1998).

Of the 16 original countries from 1995, only Norway, the Russian Federation, Slovenia, and Sweden participated in two repetitions of the TIMSS Advanced study in 2008 and 2015.

In the TIMSS Advanced 1995 specialized physics test, Norway and Sweden had the two highest mean physics achievement among participating countries. Students from the Russian Federation had the third-best results. The mean achievement of Slovenian students was also higher than the international average, but the difference was not statistically significant.

In 2008, Slovenia and Norway belonged to the group of highest-achieving countries. Students from the Russian Federation scored somewhat above the international average, and Sweden had the mean achievement lower, but very close to the international average.

Both countries, Norway and Sweden, scored reasonably high in the TIMSS Advanced 2008 specialized physics test, but their mean achievement declined compared to 1995. According to Lie et al. (2011, pp. 180) 'One important factor contributing to this decline in Sweden might be that due to a school reform the most advanced mathematics course is no longer obligatory for students studying advanced physics.' Lie et al. (2011, pp. 186) continue to interpret the reasons behind the marked decline in the TIMSS Advanced physics achievement test by discovering 'a strong effect of the degree of mathematical or algebraic manipulation implied when solving a physics problem'. Lie et al. (2011) also noticed a considerable increase in the amount of time spent doing paid jobs by 18-year-olds in both countries and the possible negative influence of doing a paid job on students' physics scores.

Norway, Sweden, and the Russian Federation had lower mean physics achievement in 2015 than in 1995. The mean achievement of Slovenian students has not changed essentially since 1995 (Mullis, 2016). However, Slovenia had the highest mean physics achievement among all participating countries, followed by the Russian Federation and Norway. Students in Sweden performed slightly lower.

Pentin et al. (2018) try to explain the decrease in the mean physics achievement of Russian students compared to previous cycles by the increase in the percentage of items on modern physics in which students performed lower than in other content areas. This content area is in the Russian physics curriculum the least covered. They also hypothesized about the increased coverage index, which indicates the percentage of young people enrolled in advanced physics programs in the country's population of the given age group (Pentin et al., 2018). According to that hypothesis, the increased number of students enrolled in advanced physics courses caused the increase in new physics teachers with a lack of experience, which could result in a lower acquired physics knowledge of the students.

In the context of the comparative international study TIMSS Advanced assessing the knowledge of students at the end of secondary school studies, it is useful to look at the school-leaving exams of the participating countries. Such a comparison will complement the picture of the focus of upper secondary education in the given countries and might help reveal the possible motivation of countries to participate repeatedly in international tests.

2.4.1 School-leaving examination in physics in Slovenia

At the end of upper secondary education, students take the school-leaving examination, which differs between study programmes. There is general Matura for students of general secondary schools (gymnasiums), vocational Matura for students of technical secondary schools, and final examination for students of vocational secondary schools (Eurydice, 2023, November 27).

School-leaving examination in physics is possible only for students of gymnasiums. It is usually chosen by 20% of final-year gymnasium students (Državni izpitni center, 2022c).

The Matura examination in physics has an external part (makes up 80% of the final mark) and an internal part (makes up 20% of the final mark). The Matura exam catalogue for physics (Državni izpitni center, 2022a) determines, among other things, what the Matura exam consists of and what curriculum it covers. The external part consists of two types of tests. The first test contains 35 multiple-choice questions, and each correct question is scored by 1 point. The second test consists of open-ended items. Of the six open-ended items, the student chooses three items that will be scored. Each open-ended item belongs into one of the areas of Measurement, Mechanics, Thermal physics, Electricity and magnetism, Oscillations, wave phenomena and optics, Modern physics and astronomy. The maximum for each open-ended item is 15 points. The internal part of the Matura exam in physics comprises laboratory work. Students must complete 8–10 laboratory works, from which they will prepare a report and submit the report to their teacher until the deadline set by the calendar of the general Matura examination (Državni izpitni center, 2022b). The laboratory works are assessed by teachers and scored maximum by 20 points.

The external part of the Matura exam in physics is prepared and assessed centrally in Slovenia, and thus its results are more objective than the results of the Matura examination in physics in the Czech Republic. After taking a look at the Matura physics tests from previous years, it can be seen that the structure of the tests and test items are very similar to the items in the TIMSS Advanced specialized physics test. We could assume that the high and stable performance of Slovenia in the TIMSS Advanced physics test is partly due to the fact that these types of test items are familiar to Slovenian students.

Slovenians are aware of the benefits provided by regular participation in international studies. Pavešić supports that by stating that 'TIMSS helped to report about the underachieving national school system and find critical gaps in the school system before a school reform. Through the school reform in the nineties, TIMSS results helped to direct the designing of new mathematics and science curricula.' (2013, pp. 51).

2.4.2 Completion of secondary school studies in Norway and Sweden

In Norway, students do not take a compulsory school-leaving examination in physics at the end of secondary school studies. According to Tveit (2014, pp. 224), 'in upper secondary education, students undertake 5–6 examinations of which 3–4 are external written examinations and 2–3 are local oral or practical examinations (programme dependent)'.

While the written examination is set and marked centrally (at national level), an oral examination is prepared and assessed by local examiners (usually students' teacher).

In Norway, they are very well aware of the importance and benefits provided by international comparative achievement surveys, because as Tveit (2014, pp. 227) argues, these surveys 'help monitor the quality of the education system in relation to new reforms and policy, and in comparison with other countries.' That could be one of the possible motivations for Norway to participate repeatedly in the TIMSS Advanced study.

In Sweden, there is no final examination at the end of upper secondary school studies. Students obtain school-leaving certificate containing grades received in the courses studied (Eurydice, 2024, January 30).

2.4.3 School-leaving examinations in the Russian Federation

Students have the possibility to take the school-leaving examination in physics at the end of upper secondary school in the Russian Federation. Citing Mullis et al. (2016): 'All final-year secondary school students have to pass two (written) mandatory Unified State Examinations (USE): mathematics and Russian language. Graduates of the Profile physics program (Grade 11) do not have to pass any mandatory examination in physics. Students take the USE in physics if they are seeking admission to university courses in physics, mathematics, chemistry, etc. The USE in physics is usually taken by about 25% of all students in the final year. Students' upper secondary school grades are not considered for university admission.'

For Russian educators, the results of the TIMSS Advanced specialized physics test 'can be treated as a small though important fragment in the big picture of science education in school' (Pentin et al., 2018).

3 The research aim

Physics intervenes in the lives of each of us. Despite this, it belongs to the group of less popular or unattractive subjects. Only a small part of Czech students choose the field in which they would study physics in the future. This is evidenced by, e.g. only 10% of students in gymnasiums and technical lyceums who choose the final examination in physics at the end of their upper secondary school studies. In the Czech Republic, apart from the results of the Matura examination in physics at the end of upper secondary education, we do not have any information about what students take away from the study of physics. Furthermore, this exam is not unified in any way at the national level.

As we have already mentioned, even the international surveys conducted among students do not specifically focus on physics. Since in the Czech Republic we do not have an objective tool for monitoring what students take away from studying physics in secondary school, we decided to use the refined methodology of the TIMSS study and repeat the TIMSS Advanced physics test from 1995 among Czech gymnasium students in 2023.

The potential of using the data that this research offers is extremely broad. The first and most natural question that occurred to us in connection with this testing was how the students' learning of physics concepts and knowledge has changed over the past almost 30 years. The research aim we have set for the purposes of this paper is to find out whether the level of physics knowledge of final-year gymnasium students in the Czech Republic has changed compared to 1995. And if it has changed, which we assume, then describe how much, or in which physics content areas, the changes were greatest. To this research aim, the research questions that this study will attempt to answer are related.

The first research question: 'Was there a significant change in the mean achievement of gymnasium students in the physics test in 2023 compared to 1995? Was the change more significant for males or females?'

The second research question will focus on achievement in the physics content areas: 'Was there a significant change in the mean achievement of students in the individual physics content areas between 1995 and 2023?'

The third question will be related to the changes in the mean achievement of students in individual test items: 'In what test items has the mean achievement of students changed the most? Is it possible to find some common characteristic of these test items?'

The fourth question will focus on the phenomenon of missing answers in open-ended items and consists of two parts: 'Has the average percentage of missing responses in open-ended items increased significantly compared to 1995?', and 'Is the decrease in mean achievement in individual test items related to students' tendency to not answer questions?'

4 Methodology

The following sections will cover the description of the TIMSS 1995 methodology and the methodological procedures applied in the repeated TIMSS Advanced 1995 physics test in 2023.

4.1 Population of students with physics in their curriculum in the Czech Republic

In the Czech Republic, the subgroup of students of Population 3 who have studied advanced mathematics and physics was made up of students in the final year of four-year gymnasiums. In total, 819 students from 90 gymnasiums participated in this part of the survey.

4.2 Characteristics of the tests

The form of the testing was exclusively in paper. The tests were developed by an international group of experts in the individual content areas based on the TIMSS curriculum frameworks (Martin & Kelly, 1996).

For Population 3, four types of test booklets were created: 1. two test booklets containing items related to mathematics and science literacy (1A and 1B), 2. three test booklets containing physics items (2A, 2B and 2C), 3. three test booklets containing advanced mathematics items (3A, 3B and 3C) and booklet 4 contained mathematics and science literacy, advanced mathematics, and physics items (Gonzalez et al., 1998).

Physics test items were divided into 4 sets labelled E, F, G, H. Sets of items are also called item clusters. The set of items labelled E was part of each physics test booklets 2A, 2B, 2C. Test 2A also contained the items labelled F, Test 2B contained the cluster of items labelled G, and Test 2C contained the set of items labelled H. The test items contained multiple-choice items to which the students responded by choosing one correct answer from a menu of 4–5 options, and then the tests included short-answer items or extended-response items. The number of test items per test booklet according to physics content area can be found in Table 3.31 of TIMSS technical report volume I (Martin & Kelly, 1996), the distribution of test items by type of answer and the total number of test items by reporting category is shown in Table 3.37 of TIMSS technical report volume I (Martin & Kelly, 1996).

For clarity, multiple-choice items made up the majority of items. Specifically, 40 of the 64 items included in the comparison of results between 1995 and 2023 were multiple-choice items, 15 items required a short answer, and 9 items were answered by students creating an extended response. Theorizing, analysing, solving problems was one of the four and most frequent performance expectation category tested by the test items (36 out of 64 items).

Number of analysed items belonging into individual content areas: 16 items were from mechanics, 15 items from electricity and magnetism, 13 items from modern physics, 11 items from the area of wave phenomena and 9 items from heat.

Since not each test item developed for the study purposes was administered to every participating student, the number of respondents differed for individual sets of items.

Sets of test items labelled G and H were released and are available to the public in the publication named Released physics items (IEA, 1995). In addition to the released items, the publication also contains the correct answers to the released items, the content and performance expectation categories of the items, and specific coding guides for the responses to the items.[3]

4.3 Repeated physics testing in 2023 – changes and differences compared to TIMSS Advanced 1995

In the TIMSS Advanced survey that we repeated in 2023, we worked with a subgroup of students from Population 3 who had physics in their curriculum. When selecting the sample, we approached the same schools that participated in the TIMSS Advanced survey in 1995 (Straková et al., 1998). Of the 90 original schools, 72 agreed to participate in repeated testing. The sample was supplemented by 10 replacement schools. In 2023, 1 804 students from 82 general secondary schools participated in the testing.

We used the same test tools as in the original study in 1995. We obtained the physics tests from the Czech School Inspectorate, which is responsible for the organization of international studies in the Czech Republic. We did not change the tests in terms of the content and formal aspects of the tested curriculum, with the exception of one test item, the context of which would be unfamiliar to current students and would put them at a disadvantage compared to students from 1995. Furthermore, we added in the tests questions about the respondent's gender and questions gathering information on whether the respondent chose to take the Matura examination in physics and whether the respondent attends an optional physics seminar in the final year of study. Eventually, we modified the final questionnaire on the use of calculators when solving the test (we shortened the original questionnaire on the use of a classic calculator and added a question on the use of a calculator on a mobile phone while completing the test).

4.4 Organization of data collection in 2023

The tests were carried out in person at the schools in paper form. There were three main test administrators who tested a total of 49 schools. The rest of the schools were tested by other colleagues from our department or closely related to it (such as pre-service teachers). All test administrators were trained and received detailed instructions on the testing process.

Before the start of the test, the administrators instructed the students how to complete the test and after that they read the test instructions inside the test before solving the test. The net testing time was 90 minutes.

Data collection was carried out from February to March 2023. One school requested testing in January 2023.

4.5 The sample of students tested in physics

In Section 2.2, we wrote that the entire class of students within one school always participated in the specialized physics test. In 1995, 819 final-year students from 90 four-year gymnasiums participated in the TIMSS Advanced specialized physics test. The females made up 59.7% and the males the remaining 40.3% of the sample. Another 268 students solved test booklet 4, which, among other test items, also contained physics items from the set of items labelled E. The test items labelled E were multiple-choice items and there were 10 of them in total. In total, in 1995, females represented 60.8% of students solving physics items and males made up 39.2%.

In 2023, 82 gymnasiums participated in the TIMSS Advanced 1995 repeated specialized physics test. One school had to be excluded from the analyses because the students took the test for only 45 minutes instead of 90 minutes.

We tested the entire class of final-year students in 74 schools. At 8 schools, only final-year students attending an optional physics seminar or a mixture of students from two or more classes were tested.[4] Due to the comparability of student samples in both tests and methodological correctness, we introduce the so-called *corrected sample of students*. From the original sample of 82 schools, for the purposes of the analyses in this paper, we excluded 9 original schools that did not meet the testing conditions. In this

[3]For Czech readers, we would like to draw attention to the publication written by Palečková et al. (1999) containing, among other things, part of the released items in Czech.

[4]We could not influence these changes in the sample of tested students. Some schools announced in advance that they would only agree to test students attending the elective physics seminar. This attitude of the schools is explained by concerns about the poor results of the students in the physics tests. At other schools, the sample was skewed only at the time of the testing itself, when the schools arbitrarily mixed up the tested students and the test administrators did not know about this change, or had no other choice and had to test the given group of students.

paper, we will present data and results for the year 2023 based on a corrected sample of 1 602 students from 73 gymnasiums. 1 429 students studied the four-year gymnasium programme at 64 schools, 78 students from 4 schools attended the six-year gymnasium, and 95 students from 5 schools studied the eight-year gymnasium study programme. In 2023, 59.7% of the respondents were females and males represented the remaining 40.3%.

4.6 Data processing

The scoring of open-ended items was carried out in accordance with uniform coding guides. We used the same coding guides as in TIMSS Advanced 1995. The open-ended item coding scheme is described in Chapter 7.5 of the TIMSS technical report volume I (Martin & Kelly, 1996). The tests in 2023 were coded by 4 independent coders. 46% of the tests were double-coded, with a 97% rate of complete code agreement.

After scoring, responses to multiple-choice items and response codes of answers to open-ended items were transcribed into an Excel spreadsheet. After the data cleaning process, the responses to the multiple-choice items and part of the open-ended items were recoded as 1 – correct answer, 0 – wrong answer. Missing answers[5] or uninterpretable answers[6] were also considered incorrect. Responses to open-ended items were recoded using a 2–1–0 scheme, where 2 indicated a completely correct response, 1 indicated a partially correct response, and 0 indicated an incorrect response to the item. The modified data set undergone statistical processing.

We computed the mean achievement as the arithmetic mean of the answers in the given test item. For the purposes of the computation of the mean achievement, only completely correct responses were treated as correct answers and partially correct answers were considered incorrect. This method of computation of the mean achievement was also used in TIMSS 1995.

To evaluate the statistical significance of the differences in the mean achievement, we used the t-test for two independent samples. We determined the substantive significance of the differences in means using the effect size index Cohen's d. To express the effect size in terms of small, medium and large, we used the definitions of the effect sizes given by Cohen (1988, pp. 25) as follows:

- small: $d < 0.5$;
- medium: $d < 0.8$;
- large: $d > 0.8$.

5 Results

All comparisons and computations of the mean achievements and outputs of tests of statistical and substantive significance discussed in this section will refer to the samples of students from TIMSS Advanced 1995 and 2023 defined in Section 4.5.

5.1 Comparison of the overall mean physics achievement

The mean achievement of Czech gymnasium students in the TIMSS Advanced specialized physics test repeated in 2023 decreased statistically significantly compared to 1995 ($p < 0.001$). In terms of substantive significance, we are talking about a medium difference ($d = 0.53$) in the mean student achievement between 1995 and 2023 (see Tab. 1). Compared to 1995, the mean physics achievement of males decreased more than the females' mean achievement. The mean achievement of males lowered by about 10%, while the mean achievement of females by about 6%.

Tab. 1: Mean physics achievement in TIMSS Advanced 1995 and 2023

The mean	TIMSS Advanced 1995		TIMSS Advanced 2023		p-value	Cohen's d
achievement	original	corrected[7]	original	corrected[7]		
Overall	38.6%	38.6%	30.8%	30.8%	< 0.001	0.53
Females	34.2%	34.2%	27.9%	27.9%	< 0.001	0.51
Males	45.5%	45.5%	35.3%	35.3%	< 0.001	0.63

[5]If the test item was administrated to the student, but the respondent did not solve the given item, the response was coded as 'missing answer'.

[6]The respondent chose two or more responses from the given offer of the answers.

[7]In Sections 2.3 and 4.2, we wrote about a cluster-based design of the tests. It means that not each test item was administered to every respondent. This could have caused that different sets of items (E, F, G, H) were assigned to groups of students differing in mean physics achievement. For this reason, in addition to the original means, we also included in the table the corrected means, from which the statistical and substantive significance of the differences between means were subsequently evaluated. The corrected mean was calculated from the original mean by correction to the so-called average student, by which we mean what would be the mean achievement of such a student in the given group of items.

5.2 Changes in the mean achievement in individual physics content areas

The comparison of student performance in all five physics content areas between the years 1995 and 2023 is presented in Tab. 2. Students' mean achievement lowered the most in mechanics and heat.

Tab. 2: Mean achievement in physics content areas

Physics content area	TIMSS 1995 mean achievement		TIMSS 2023 mean achievement		p-value	Cohen's d
	original	corrected[7]	original	corrected[7]		
Mechanics	44.8%	44.8%	32.3%	32.3%	< 0.001	0.52
Electricity and magnetism	36.4%	36.4%	30.7%	30.7%	< 0.001	0.30
Heat	39.7%	39.7%	27.0%	27.0%	< 0.001	0.46
Wave phenomena	40.0%	40.0%	32.9%	32.9%	< 0.001	0.30
Modern physics	34.8%	34.8%	32.0%	32.0%	0.003	0.12

In terms of mechanics, students' mean achievement lowered especially in items F04 (decrease of 15.3%), F17A (decrease of 21.2%) and G08 (decrease of 16.9%). In terms of heat, the biggest differences in mean achievement are observed in items E08 (decrease by 21.3%) and F05 (decrease by 20.5%). Descriptions of all the five mentioned test items are presented in Tab. 3.

Tab. 3: Descriptions of items with the largest differences in mean achievement between 1995 and 2023

Item	Item description
E08	choice of the best estimate of the number of molecules of air in the room
F04	determination of the speed of the aircraft at the highest point of its circular trajectory in the vertical plane
F05	determination of the process by which energy from the Sun is transferred to Earth
F07	determination of the cause of the smaller kinetic energy of the emitted electron compared to the kinetic energy of the incident photon in the photoelectric effect
F08	determination of the two light bulbs using the least power out of nine light bulbs in a composite direct current circuit
F13	calculation of the wavelength of waves in shallow water based on the known wavelength of waves in deep water and known values of the speed of movement of waves on the water surface in shallow and deep water
F17A	calculation of the value of gravitational acceleration using the values given in the graph of the dependence of the height of the fall of the object on the second power of time
G08	determining the correct graph describing the dependence of the total mechanical energy of an oscillating block (and the spring on which it oscillates) on the length of the spring
H02	determining the only correct one of the four statements about evaporation of a liquid
H03	identifying the graph of the dependence of the maximum kinetic energy of the emitted electrons on the frequency of incoming radiation during the photoelectric effect for metal with a work function which is less than the work function of metal for which the reference graph in the assignment is made
H05	determination of the length of a spaceship passing an observer at a speed close to the speed of light when knowing the length of the spaceship at rest before it took off
H15	calculation of the wavelength of an electron travelling with a certain speed
H19B	stating a possible reason for the different results of the experiment used to measure the speed of sound using echos on the playground wall in four different teams of students

The item descriptions were provided by Straková et al. (1998).

Cohen's d value confirms the significant decrease in mean achievement, especially in mechanics. The value of 0.52 represents a medium difference in the mean achievement between 1995 and 2023. The effect sizes (see Tab. 2) for the performance in the rest of the physics content areas represent a small difference in the mean achievements between 1995 and 2023, although all differences in means are statistically significant.

5.3 Characteristics of items with the greatest changes in mean achievement

Tab. 3 contains descriptions of 13 items in which the differences in mean achievement[8] between 1995 and 2023 were greater than 10%. We observe a lowering of the mean achievement in all these items, see Tab. 4.

[8] The percentage of (completely) correct answers represents the mean achievement of students in the given test item. We described the computation of the mean achievement in Section 4.6.

Tab. 4: Characteristics of the items with the largest decrease in mean achievement

Item	Item type	Physics content area	Subject-matter content	Performance expectation	Changes in means: (−) decrease / (+) increase	
					Correct response	Missing response
E08	Multiple-choice	Heat	Physics changes	Theorizing, analysing, solving problems	−21.3%	1.0%
F04	Multiple-choice	Mechanics	Dynamics of movement	Theorizing, analysing, solving problems	−15.2%	1.7%
F05	Multiple-choice	Heat	Heat and temperature	Understanding	−20.4%	0.4%
F07	Multiple-choice	Modern physics	Quantum theory and elementary particles	Understanding	−20.1%	1.7%
F08	Multiple-choice	Electricity and magnetism	Electricity	Theorizing, analysing, solving problems	−12.8%	1.1%
F13	Short-answer	Wave phenomena	Wave motion	Theorizing, analysing, solving problems	−20.8%	25.3%
F17A	Extended-response	Mechanics	Time, space and motion	Investigating the natural world	−21.2%	13.2%
G08	Multiple-choice	Mechanics	Types of forces	Using tools, routine procedures, and science processes	−16.9%	2.1%
H02	Multiple-choice	Heat	Explanation of physics changes	Understanding	−10.4%	1.5%
H03	Multiple-choice	Modern physics	Quantum theory and elementary particles	Using tools, routine procedures, and science processes	−14.9%	1.1%
H05	Multiple-choice	Modern physics	Theory of relativity	Theorizing, analysing, solving problems	−12.9%	2.8%
H15	Short-answer	Modern physics	Quantum theory and elementary particles	Theorizing, analysing, solving problems	−10.1%	33.8%
H19B	Extended-response	Wave phenomena	Sound	Investigating the natural world	−15.5%	8.7%

The item characteristics are based on the TIMSS science curriculum framework (Robitaille et al., 1993).

The most common content area of items with a high drop in mean achievement was modern physics. Most of these tasks were multiple-choice items. The most frequent performance expectation category of items with a high drop in mean achievement was theorizing, analysing, solving problems.

Despite these most frequent characteristics of the 13 selected items, the two biggest changes, or decreases in the mean achievement between 1995 and 2023 are observed for open-ended items F13 and F17A (see Tab. 3 and Tab. 4).

5.4 Changes in the average percentage of missing responses in open-ended items

The average percentage of missing answers in open-ended items was approximately 31.7% in TIMSS Advanced 1995, rising to 46.1% in 2023 (see Tab. 5[9]). This represents an increase of 14.5%. Likewise, the median values in Tab. 5 prove the significant increase in the percentage of missing answers in open-ended items between 1995 and 2023. While in the TIMSS Advanced 1995 specialized physics test half of the open-ended test items were not answered by 28.5% of respondents, in 2023 the proportion of such students increased to 51.0%.

[9]The total sum of correct, partially correct, incorrect and missing answers may differ from 100% by tenths of a percent for some test items due to rounding.

Tab. 5: Changes in the proportions in individual response categories in open-ended items

Item	Correct responses		Partially correct responses		Incorrect responses		Missing responses		Changes in the proportions in individual response categories: (−) decrease / (+) increase		
	1995	2023	1995	2023	1995	2023	1995	2023	Correct	Incorrect	Missing
F12	14.9%	8.6%	4.9%	4.1%	51.1%	33.3%	29.1%	54.1%	−6.4%	−17.8%	25.0%
F13	50.6%	29.7%			31.8%	27.3%	17.6%	42.9%	−20.8%	−4.5%	25.3%
F14	7.1%	3.9%	14.5%	8.2%	19.3%	13.8%	59.1%	74.2%	−3.2%	−5.6%	15.1%
F15	8.2%	3.3%	5.6%	1.5%	29.5%	34.8%	56.7%	60.4%	−4.9%	5.3%	3.7%
F16	2.2%	1.7%	1.5%	1.5%	19.3%	14.5%	77.0%	82.3%	−0.6%	−4.8%	5.4%
F17A	34.9%	13.8%			17.1%	25.1%	48.0%	61.2%	−21.2%	8.0%	13.2%
F17B	7.8%	3.5%			22.0%	10.0%	70.1%	86.4%	−4.3%	−12.0%	16.3%
G11	4.3%	4.6%	12.0%	20.0%	80.4%	62.2%	3.3%	13.1%	0.3%	−18.2%	9.9%
G12	13.8%	10.4%	9.1%	7.0%	48,6%	32.4%	28.6%	50.2%	−3.4%	−16.1%	21.6%
G13	4.0%	9.3%			89.1%	74.4%	6.9%	16.3%	5.3%	−14.7%	9.4%
G14	13.8%	5.4%			39.9%	31.3%	46.4%	63.3%	−8.4%	−8.6%	17.0%
G15	4.3%	1.9%			90.2%	79.8%	5.4%	18.3%	−2.5%	−10.4%	12.9%
G16	2.9%	3.9%	68.5%	50.7%	26.4%	28.9 %	2.2%	16.5%	1.0%	2.4%	14.3%
G17	26.1%	22.8%			52.5%	39.4%	21.4%	37.8%	−3.3%	−13.1%	16.4%
G18	1.8%	3.0%	8.0%	4.6%	43.8%	39.3%	46.4%	53.1%	1.2%	−4.6%	6.8%
G19	2.5%	5.4%	5.1%	3.9%	81.2%	65.7%	11.2%	25.0%	2.8%	−15.4%	13.8%
H12	12.8%	10.1%			86.5%	79.8%	0.7%	10.1%	−2.7%	−6.7%	9.4%
H13	17.2%	11.6%			63.1%	54.2%	19.7%	34.2%	−5.5%	−8.9%	14.5%
H14	9.1%	9.0%	43.8%	32.8%	46.7%	48.9%	0.4%	9.4%	−0.2%	2.1%	9.0%
H15	26.3%	16.2%			52.6%	28.8%	21.2%	55.0%	−10.1%	−23.7%	33.8%
H16	13.5%	4.2%	1.1%	0.8%	17.9%	13.2%	67.5%	81,9%	−9.3%	−4.7%	14.4%
H17	5.8%	3.1%	3.3%	0.6%	62.4%	45.8%	28.5%	50.6%	−2.8%	−16.6%	22.1%
H19A	7.7%	4.0%	13.9%	8.0%	28.5%	28.4%	50.0%	59.5%	−3.7%	0.0%	9.5%
H19B	37.6%	22.1%			19.6%	26.3%	42.8 %	51.5%	−15.5%	6.8%	8.7%
Mean	13.7%	8.8%					31.7%	46.1%	−4.9%	−7.6%	14.5%
Median					28.5%	51.0%					

The change in the proportion of incorrect responses to the H19A test item is equal to −0.03% after rounding to two decimal places.

5.5 Connection between the mean achievement drop in open-ended items and the students' tendency to omit answers

In addition to changes in the proportions of correct and incorrect responses, changes in the proportions of missing answers are also depicted in Tab. 5. The blue colour of the data bars represents a positive number, and the red colour indicates a negative number in the cell. The darker the colour of the cell bar, the higher the absolute value of the number in the cell. Colours and saturations of the data bars in Tab. 5 indicate a connection between an increase in missing responses and a decrease in mean achievement[8] in open-ended items. The most significant changes in the percentages of correct and missing answers are observed in items F13, F17A, G14, H15, H16 and H19B. The text of items from clusters G and H can be found in the publication with released physics items (IEA, 1995).

In Tab. 5 it can be seen that in 15 of 24 items (F12, F13, F14, F16, F17B, G12, G14, G15, G17, H12, H13, H15, H16, H17, H19A) the decrease in mean achievement[8] was not followed by an increase in incorrect answers. For these items, the decrease in mean achievement was primarily caused by an increase in the percentage of missing answers. Even for some items, the proportion of incorrect responses decreased.

The above-mentioned changes in the proportions of missing, correct and incorrect answers in open-ended items support the conclusion that the decrease in the mean physics achievement[8] in these questions is related to the increase in the percentage of missing answers.

6 Discussion of results

The difference in mean achievement in the physics test was statistically significant in 2023 compared to 1995. The significance of the differences in means was also determined by the size of the samples of the tested students, but it was also proved by Cohen's d in Tab. 1 and Tab. 2.

This study focused on the basic evaluation of the results of Czech gymnasium students in the repeated TIMSS Advanced physics test and on the initial comparison of the results from 2023 with the results of students from 1995. It did not aim to explain the differences in results or find their cause. Nevertheless, we consider it appropriate to briefly discuss the changes in the Czech education system since 1995 and to answer the hypothesis expressed by many physics teachers in an attempt to explain the worsened results of gymnasium students in the physics test through the changes that have taken place in the school education system since 1995.

The reform process of the Czech education system since 1990 enabled steps to liberalize the content and organization of education. The autonomy of schools in the area of curriculum creation was strengthened.[10] People from practice and the field of education, especially physics teachers and school principals, objected that since 1995 the time allotment for physics in upper secondary schools in the Czech Republic has decreased, and therefore the results are not surprising. In 2021, we conducted a questionnaire survey (Pschotnerová & Mandíková, 2024) among general secondary schools and upper secondary schools with the study programme technical lyceum in the Czech Republic, where, among other things, we investigated the time allotment for physics in individual years of study. We found that the average time allotment for physics in the upper gymnasium[11] is 2 lessons per week in the first three years of study, and physics is no longer compulsory in the final year. Instead, in the last two years of study, the time allotment for optional seminars is strengthened, in which students can also study physics and deepen their knowledge. In the 1991 curriculum, the time allotment for physics for the general gymnasium study programme was 3 lessons per week in the 1st and 2nd year, and 2 lessons per week in the 3rd and 4th year (Ministerstvo školství, mládeže a tělovýchovy ČR, 1991). Since 1992, a new curriculum began to apply, where the minimum time allotment for physics for a four-year gymnasium was reduced to a minimum of 2 hours per week, while in the 4th year the time allotment for physics was already determined by school principals (Ministerstvo školství, mládeže a tělovýchovy ČR, 1992). It is obvious that one of the reasons for the decrease in the mean achievement of Czech gymnasium students in the physics test may be the reduced time allotment for physics.

Moreover, the proportion of students attending gymnasiums in the Czech Republic has changed compared to 1995. While in 1995, 10.8% of the population completed four-year gymnasium,[12] in 2023 it was 19.9% of the corresponding population.[13] The proportion of students attending gymnasiums has doubled and may have caused the quality of gymnasium students to drop.

After evaluating the differences in mean achievement in the items from the individual physics content areas, the substantive significance test showed the largest differences in student knowledge in the area of mechanics. When we looked in more detail at the items with the biggest differences in mean achievement, it turned out that more than 10% decrease in mean achievement appeared most often in items from the content area of modern physics. Thus, it seems that even such a radical drop in the mean achievement in the units of test items did not affect the overall mean achievement in items from the area of modern physics.

When scoring open-ended items, we noticed that a large part of the answers was missing. Students omitted answers to open-ended items. So we naturally asked whether this phenomenon of missing answers to open-ended items is not related to a decrease in the mean achievement in open-ended items. As shown in Tab. 5 and the shifts in the proportions of individual answer categories, our hypothesis was confirmed. In 15 items out of 24, at the same time as the proportion of correct answers, the proportion of incorrect answers also decreased, compensated by an increase in the proportion of missing answers. It is beyond the scope of our research to find out why students did not answer open-ended items to an increased extent compared to 1995. One of the possible reasons for the increase in missing answers could be the fact that today's young people generally do not like to formulate more complex texts. They are used to a brief conversation through social media that uses shorthand phrases.

In 1995, 16 countries participated in the TIMSS Advanced physics test (Mullis et al., 1998). In TIMSS Advanced 2008, the number of participants decreased to nine and changed compared to 1995 (Mullis et

[10] The main difference between the curriculum and the Framework education programme (FEP) is that the curriculum of that time for specific education programme was identical for all schools in the Czech Republic. Today's FEPs set the basic requirements for the education of primary and secondary school students by the state. On the basis of the FEP, schools develop their school education programmes, where they already specify the content of education in individual subjects and their time allotment in specific years of study.

[11] In the Czech Republic, there are eight-year, six-year and four-year gymnasium study programmes. Students enter each of them at a different age, but the age of completion is the same for all. By upper gymnasium we mean the last four years before completing the upper secondary education, e.g. all 4 years of a four-year gymnasium or the third to the sixth year of a six-year gymnasium or the fifth to the eighth year of an eight-year gymnasium study programme.

[12] In the school year 1994/1995, 19 348 students completed the four-year gymnasium study programme. The population of 18-year-old residents of the Czech Republic was 179 592 citizens as of July 1, 1995 (Outrata et al., 1996).

[13] In the school year 2022/2023, 21 576 students completed gymnasium study programmes (Sekce informatiky, statistiky a analýz MŠMT, 2023). The population of 18-year-old residents of the Czech Republic was 108 329 citizens as of December 31, 2022 (Rojíček et al., 2023).

al., 2009). Nine countries participated in the TIMSS Advanced 2015 physics test (Mullis et al., 2016). Only regular participants could monitor the trend in physics achievement of their students.

The decreasing mean achievement in the TIMSS Advanced specialized physics test is not rare only in the Czech Republic. Over the 20 years, the mean physics achievement of students from the TOP performing (and regularly participating) countries like Norway, the Russian Federation and Sweden decreased too. Only the results of Slovenian students did not worsen.

It is obvious that the number of participants in the TIMSS Advanced study is decreasing. Our research can serve as an inspiration for countries that have not participated repeatedly in the TIMSS Advanced physics test and are interested in the trend of learning physics concepts among final-year students of upper secondary schools.

7 Limitations of the research

We are aware of several limitations of our research.

We may not have been able to replicate the research completely. The original sample of schools from 1995 was partially changed. Of the original 90 schools, 72 gymnasiums participated in the repeated survey. Of these, one school was not included in the analysis of the results because they did not provide students with sufficient testing time. We supplemented the sample with 10 replacement schools. The corrected sample, which is the basis of this paper, consisted of 73 schools (of which 63 were the original schools).

In the TIMSS Advanced 1995 specialized physics test, only final-year students of the four-year gymnasiums were tested. The structure of schools and study programmes taught in the Czech Republic has changed somewhat over the years. At five of the original 72 schools, the four-year gymnasium study programme is no longer taught and has been replaced by an eight-year (four schools) and a six-year gymnasium study programme (one school). At another three schools, instead of students of a four-year gymnasium study programme, students of the final year of a six-year gymnasium were tested, and at another two, students of an eight-year gymnasium participated in the testing. It is important to add that the framework educational programmes for the upper gymnasium[11] are identical. Therefore, this change in the replacement of students from the four-year gymnasium by the students from multi-year gymnasium study programmes in 10 schools (in the case of the corrected sample of schools in 9 schools) should not affect the mean achievement in the physics test.

The mean achievement of the students in the physics test was probably also influenced by the students' motivation, which was naturally reflected in their performance in the test. This is evidenced by the increase in the proportion of missing answers. Today, students participate in various tests quite often. In 1995, TIMSS was the first huge international research, so their motivation was naturally higher.

For multiple-choice items, we cannot distinguish whether the student arrived at the answer through cognitive processes, copied the answer from a classmate, or chose it randomly. But that could also have happened in 1995.

One of the research limitations is clearly the impossibility of following up on an international comparison of the results of Czech students with the results of students from other countries. We carried out this testing separately, without any follow-up to other assessments, since in another of the previously participating countries in the TIMSS Advanced specialized physics test, the same testing did not take place at the recent times.

8 Conclusions

In the paper, we present the first results of the TIMSS Advanced 1995 specialized physics test repeated in 2023. Specifically, the results of the so-called corrected sample, which consisted of 1602 final-year students of 73 gymnasiums. In the original testing in 1995, 819 respondents from 90 gymnasiums took part, and another 269 respondents solved 10 multiple-choice items from physics within the test booklet 4 administered to other final-year students of gymnasiums.

The answer to the first research question is clear. The mean achievement of Czech gymnasium students in the TIMSS Advanced specialized physics test dropped significantly between 1995 and 2023 (see Tab. 1). This negative change in achievement was more significant for males, whose mean achievement decreased by about 10%, while females worsened by approximately 6%.

Students' knowledge of physics decreased in all content areas (see Tab. 2). The drop in the mean achievement occurred mainly in the knowledge of physics concepts in the area of mechanics.

The majority of the analysed items consisted of items from mechanics (16), then from electricity and magnetism (15), from modern physics (13), then from the area of wave phenomena (11) and the least items were from the content area of heat (9). Items from the area of modern physics made up the majority of the 13 items where the drop in the mean achievement was higher than 10%. It is therefore obvious that this phenomenon was not due to a relatively higher number of items from the area of modern physics among other items. The relatively higher number of multiple-choice items and items eliciting theorizing, analysing, solving problems may have influenced the fact that these characteristics were the most frequent characteristics of 13 test items with more than a 10% decrease in the mean achievement of students.

A more detailed analysis of shifts in the proportions of correct, incorrect and missing answers for open-ended items showed that the decrease in the mean achievement of students in these items is caused by a significant increase in the average percentage of missing answers. In 1995, 31.7% of students did not answer open-ended items, in 2023 their portion rose to 46.1% (see Tab. 5).

The conclusions stated above fulfilled the research aim set in this paper and answered all formulated research questions.

The data obtained in the testing provide a wide spectrum of information on the knowledge of physics concepts of students in the final years of general secondary schools in the Czech Republic. In the future, we plan to continue working with the data and to use its rich informational potential. Also using the IRT method, we will analyse the results of the students in the tests in more depth, compare them, and publish the conclusions.

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