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Integrated STEM in secondary education: A case study

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Summary. — Despite many opportunities to study STEM (Science, Technology, Engineering & Mathematics) in Flemish secondary education, only a minority of pupils are actually pursuing STEM fields in higher education and jobs. One reason could be that they do not see the relevance of science and mathematics. In order to draw their pupils' interest in STEM, a Belgian school started a brand new initiative: the school set up and implemented a first year course that integrates various STEM disciplines, hoping to provide an answer to the question pupils often ask themselves about the need to study math and science. The integrated curriculum was developed by the school's teachers and a STEM education research group of the University of Leuven. To examine the pupils' attitude towards STEM and STEM professions and their notion of relevance of STEM at the end of this one-year course, a post-test was administered to the group of pupils who attended the integrated STEM course (the experimental group) and to a group of pupils that took traditional, non-integrated STEM courses (the control group). The results reveal that attending the integrated STEM course is significantly related to pupils' interest in STEM and notion of relevance of STEM. Another post-test was administered only to the experimental group to investigate pupils' understanding of math and physics concepts and their relation when taught in an integrated way. The results reveal that the pupils have some conceptual understanding and can, to a certain extent, make a transfer of concepts across different STEM disciplines. However, the test results did point out that some additional introductory training in pure math context is needed.

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1. – Introduction

In secondary education in Flanders (Belgium) pupils have a variety of options to study one or more disciplines of STEM (Science, Technology, Engineering, Math). This STEM education is often considered to be of relatively high quality, since Flemish pupils perform above average in international assessment studies (De Meyer *et al.*, 2013; 2014). Although the educational environment seems beneficial for Belgian pupils, they are often not intrinsically motivated for STEM (Schleicher and Davidson, 2013).

A study that investigates the relevance of science education (ROSE), points out that 15 year old pupils feel that they can personally influence what happens in the environment, but that they do not think science and technology are tools that can be used to solve environmental problems (Sjøberg and Schreiner, 2010). One might ask whether this discrepancy and lack of motivation for STEM can be due to education. The ROSE-study seems to corroborate this assumption: in most European countries, youngsters rather disagree with the statement "School science has shown me the importance of science for our way of living" (Sjøberg and Schreiner, 2010).

This indifference towards STEM education seems to result in a mismatch between the educational system and industry. To meet the need of the industry, too few people graduate with a STEM degree: in Flanders only 19.0 percent of the students in higher education. That is only half of the pupils that finish secondary school with a STEM diploma (41.1 percent). The decrease does not stop there; only six out of ten people with a STEM diploma actually apply for a STEM job (Van den Berghe and De Martelaere, 2012).

To stress the relevance of science and math, we think that it is important in the first place to show the interrelatedness between the STEM disciplines. While this seems obvious, it is not yet always done in the current Flemish educational system. This paper sheds light on an initiative, taken by a Flemish secondary school: a new study program in its first year, with a course "STEM". This exploratory study is the first phase in testing our hypothesis that integration of STEM disciplines can provide an answer to pupils' perception of missing relevance. Our research question was twofold: 1) Can we motivate pupils for STEM and STEM jobs and show them the relevance of STEM by teaching math and science in an integrated manner? 2) Can we teach them in this early stage of secondary education, in an integrated way, mathematical concepts like graphs, tables, formulas and functions, and physics concepts like position, velocity and acceleration?

The paper starts by situating the organisation of the new STEM initiative in the first year of secondary education and the curriculum development. We made a deliberate choice of three learning paths, which will be expanded throughout the six years of secondary education. The paper zooms in on the learning path Mechanics in the following section. To evaluate the impact of the new didactic approach, two post-tests were developed: one to examine pupil understanding of some of the STEM topics learned, and another one to verify the attitude of the pupils towards STEM after one year of STEM education. The paper discusses the research method and elaborates on the results in the next section. Finally, it ends with the conclusions that can be drawn from the results, and the future perspectives.

2. – A new study program "STEM"

2·1. *Organisation.* – In order to enhance the attitude of its pupils towards STEM, a school in Flanders (Belgium), set up a brand new study program, called "STEM", in the first year of its secondary education. This program is organized next to the existing program, in the following referred to as "non-STEM". Every course in the non-STEM program is instructed in the traditional non-integrated way. The pupils who opt for the study program STEM, are instructed integrated abstract STEM through a course of five hours a week. 21 pupils enrolled in this program in the academic year 2013-2014, amongst whom 5 girls. They form two groups, which are each instructed by two teachers at the same time. The teachers have different educational backgrounds, which facilitates integrated approaches. For the content of this course, the school's teachers turned to the University of Leuven (Belgium) for support and cooperation.

2·2. *Didactical approach.* – In the new study program, a new teaching/learning approach is practised, in which a high level of understanding of abstract science, math and technology is aspired, a competence within STEM literacy. Moreover, a key concept to achieve the goal of demonstrating the relevance of STEM for environment and society, is the integration of the different STEM-disciplines. This means that one of the learning goals is to show the interplay of STEM disciplines in their daily quest to address the burning issues of today's society.

The development of the curriculum is inspired by the "Making Learning Whole" principle (Perkins, 2009). The idea is to keep a holistic view on the content that is to be instructed. For example: rather than to be silent about acceleration until the moment the pupils have finally learned how to calculate differentials, it makes much more sense to teach the concept of acceleration right after the concepts velocity and position are instructed. After all, acceleration is basically a prolongation of the previously seen concepts. Another way of practising this Making Learning Whole principle, is to let pupils work with *whole systems*, instead of just elaborating excessively on the small blocks of which these systems consist, without showing their purpose. For example: instead of telling pupils about sensors and flip-flops, what they look like and how they work, the pupils will learn much more while using these components to build a miniature train that makes actions based upon programmed decisions. In this approach, adapted to the age of the learners, every pupil can learn to play the whole game of engineering (Dehaene *et al.*, 2013). Ultimately, this is how pupils learn to use abstractions like data, systems and processes, in order to design, analyse and validate a complete technical system.

2·3. *Curriculum content.* – For the course STEM, we opted for three well considered learning paths: Mechanics, Programming and Design.

Mechanics offers a great way to operationalize and thus integrate some mathematical concepts like graphs, functions, variables and formulas. Some of these concepts can easily be approached intuitively or qualitatively in the context of kinematics. Through mechanics, pupils not only learn how to set up an experiment, to measure and analyse data. They also learn to quantify what's going on in real life (*e.g.* continuous motion) and formulate a deliberate conclusion based on a table of data points, a graph or an expression. Moreover, representing information is one of the first steps in modelling, a competence we consider as important while "doing STEM". Pupils' design projects will often involve some kind of mechanical motion, another good reason for mechanics to be the scientific starter within the curriculum. In the scope of this paper, we will focus on the learning path Mechanics.

Programming, which demands logically and structured thinking, is an essential skill in a pupil's toolbox, since it provides him/her with the flexibility to handle all kinds of innovations in a responsible way, the entrance ticket to the increasing digital world. Furthermore, programming a robot adds an element of motivation to the integrated STEM.

Finally, *Design* is a part of integrated STEM that brings different kinds of math, science and technology disciplines together in the E of engineering. The key factor in purposeful design (Sanders, 2009) is the problem based dimension, in which pupils need to deploy their understanding of math, science and technology in order to solve the stated problem.

In the first year of the STEM course, the contents of these learning paths start with a basic package, taking into account the limited prior knowledge a 13 year old pupil possesses. We want to expand the content of the three learning paths for the six years of secondary school:

- The level of abstraction has to increase
- The degree of difficulty of math and science has to increase
- The amount of integrated science disciplines (other than physics *e.g.*) has to increase.

Teaching of the separate STEM courses, such as math, physics, chemistry and biology will be continued in the higher years too, to respect the pure nature of these disciplines as well. Nevertheless, the link to the integrated approach must be within reach for the pupils in any case.

2˙4. *Mechanics in the STEM course.* – Research has pointed out persisting difficulties for pupils in kinematics. In many cases, the understanding of kinematics concepts of graduating secondary school pupils turns out to be not sufficient in university STEM studies. Often, students mix up the concepts position and relative velocity, or the concepts velocity and acceleration (Trowbridge and McDermott, 1980; 1981). In some cases, students are held back by the idea of using their math knowledge in a context of physics (Woolnough, 2000). Furthermore, because pupils in secondary school almost exclusively encounter graphs through the origin (0,0) in a kinematics context, they are often not able to calculate the slope of a random linear graph correctly (Wemyss and van Kampen, 2013). These research results were taken into account while developing the learning path of Mechanics and the appropriate exercises. By starting in an early stage with pupils whose study program traditionally does not address this topic yet, we hope to establish a thorough and sustainable understanding of kinematics and a mutual transfer of math and physics concepts.

First the pupils learn in an interactive way about ordered pairs, function expressions and graphs. In pairs they perform an experiment, in which one pupil runs with a barrier tape in his/her hand and the other places dots on the unrolling tape each second (fig. 1). The pupils analyse the resulting tapes afterwards based upon their observations during the real life experiment. This offers a very intuitive way of defining velocity as the covered distance over the time interval, as well as the concept of acceleration. Moreover, these phenomena can be demonstrated in an abstract yet visual way, as can be seen on the right-hand side of fig. 1 (Vanden Bosch, 2008). Thorough practice in constructing and interpreting all kinds of abstract representations (graphs, formulas, tables) of different

Fig. 1. – Experiment performed by the pupils (Vanden Bosch, 2008): one pupil runs, holding a barrier tape, the other one puts dots on the tape every second (left), they cut the barrier tape at the dots and place the bars next to each other in order to construct a graph (right).

motions, helps the pupils in stating implications for real life, or vice versa. By studying the relation between the graphs of position, velocity and acceleration as a function of time, they even find out how to construct one graph based on the other one. Guided by their teacher, the pupils derive the formulas of a uniformly accelerated linear motion, in this way performing mathematical actions in a context of physics.

3. – Research method

Our research concerned the effect of teaching STEM in an *integrated* manner: 1) can we as such motivate pupils for STEM and show them the relevance of STEM?, and 2) can we as such give them in this early stage of secondary education, some understanding of math concepts like graphs, formulas and functions and physics concepts like position, velocity and acceleration?

3˙1. *Participants*. – Two classes have been surveyed: the STEM class (experimental group) and a non-STEM class (control group). Pupils of both classes participate in the same non-STEM courses. Table I shows for both classes the weekly schedule of the non-integrated STEM courses. However, pupils enrolled in the STEM program are offered a course "STEM" of five hours a week, which *does* integrate various STEM disciplines (math, physics and technique).

Five girls and 16 boys were enrolled in the STEM class, whereas 14 girls and 9 boys were enrolled in the non-STEM class. This difference in gender distribution indicates that boys are likely more interested in studying STEM than girls, and needs to be taken into account when interpreting our results.

Table I. – *Hours per week for each STEM course in the two study programs in the first year of general secondary education (Flanders, Belgium).*

Course	STEM	non-STEM
Mathematics	5	6
Natural Sciences	2	2
Technique		2
STEM	5	

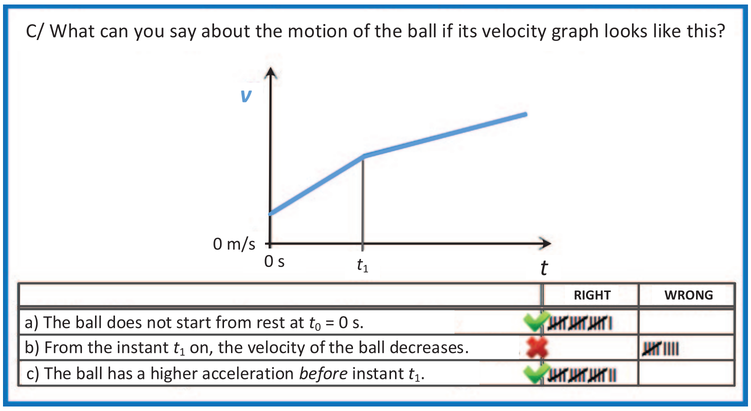

Fig. 2. – A question in the first exercise of the cognitive test: pupils had to cross either "right" or "wrong". (Here, the signs indicate the correct answers, correct answering pupils were tallied.)

3˙2. *Research design.* – To investigate the relationship between integrated STEM education and STEM literacy, we used a post-test only design. We measured *conceptual understanding in STEM* by means of a cognitive test focusing on mechanics. This test was offered to the pupils in the STEM class only because the non-STEM pupils were not exposed to STEM education concerning physics concepts. More in-depth research will be required to develop appropriate instruments allowing to compare pupils who are and pupils who are not exposed to integrated STEM education.

To investigate the relationship between integrated STEM education and *attitudes towards STEM*, we used a post-test design with a non-equivalent control group. Pupils in the STEM class and pupils in the non-STEM class filled in a survey containing 25 items.

Even though the rollout of an integrated STEM course required a lot of effort, it had to be done in a very short time period. We are aware that lack of a pre-test, which would allow to control for initial differences between pupils of the two groups, makes causal inferences rather difficult.

Table II. – *Items and reliability statistics (Cronbach's alpha) for five indexes measuring pupils' attitude towards STEM.*

Indexes	Reliability
General interest towards STEM	0.671
Job expectations with regard to STEM	0.859
Belief in gender differences with regard to STEM	0.956
Seeing the relevance of STEM	0.663
Progress in understanding STEM	0.555

3˙3. *Instruments and analysis techniques.*

3˙3.1. Cognitive test on mechanics. The cognitive test was a summative written evaluation on the topic of mechanics, as being one of the main learning paths within the integrated STEM course. It offers an objective way of assessing pupils' conceptual understanding, transfer and integration of math and physics concepts. Spread over four

TABLE III. – *Some of the items examined in the cognitive test and the percentage of correct answers by the STEM pupils ($N = 21$) (Graphs, tables or formulas are referred to as abstract representations).*

Item	Correct answering (%)
Interpreting graphs correctly	60.0
Interpreting abstract representations to physical reality	63.0
Translating physical reality into abstract representation	9.4
Switching between forms of representation: graph to formula	7.4
Switching between forms of representation: formula to graph	11.9
Switching between forms of representation: graph to table	63.0
Calculating correctly the slope $\Delta x/\Delta t$	28.4
Transfer of concepts, *e.g.* formulas: integrated to pure math context	16.0

exercises, 14 items were evaluated (see table III). The first exercise had five graphs with quotes, to be answered by "right" or "wrong". The aim was to evaluate the ability of the pupils to interpret graphs in a correct way, as shown *e.g.* in fig. 2.

The second exercise pictured the graph of the water tank level, gradually decreasing in time, to be transformed into a table of data points (Wemyss and van Kampen, 2013). The exercise checked if the pupils could deduct from the graph or table that the level was decreasing at constant speed, and whether or not the pupil used the formula of average velocity to calculate this speed. In the third exercise the pupils needed to use formulas and make calculations based on the description of a real life situation in order to construct the graphs of velocity and of position in time. In the second as well as in the third exercise the pupils' ability of switching between different kinds of representation was evaluated. The last exercise verified if pupils were able to construct a graph based on a formula in a pure math context, *e.g.*: $y = 5\ (1 - x)$, and so make the transfer of what they learned in the integrated math-science context.

One person tallied the correct answers using a coding scheme (as *e.g.* in fig. 2). Per evaluated item (table III), the average percentage of correct answers was calculated over the different exercise questions, because each exercise question examined multiple items.

3·3.2. Survey on the attitude towards STEM. Pupils in both classes were requested to fill in a survey with 25 items (4-point Likert scale), measuring various dimensions of their attitude towards STEM including cognitive beliefs, affective states and behaviour (cf. De Winter *et al.*, 2010; van Aalderen-Smeets *et al.*, 2011). Based on factor analysis and 23 items, in the end five indexes were produced: general interest towards STEM, job expectations with regard to STEM, belief in gender differences, seeing the relevance of STEM and progress in understanding STEM. The reliability coefficient, Cronbach's α, of the five indexes varies between .55 and .86 (table II).

With regard to attitudes toward STEM, we applied linear regression analysis (OLS) to investigate to what extent pupils' attitude toward STEM can be predicted by enrolment in a STEM class, controlled for gender (table IV). Standardized coefficients are presented and considered to be statistically significant if the p-value is below .05.

TABLE IV. – *The five indexes of attitude towards STEM, regressed on model 1: enrolment in the STEM class, model 2: gender, and model 3: the interaction between gender and enrolment (standardized regression coefficients).*

	General interest in STEM			Job expectations			Belief in gender differences		
	model 1	model 2	model 3	model 1	model 2	model 3	model 1	model 2	model 3
STEM	0.603***	0.464***	0.206	0.535***	0.399**	−0.183	0.145	−0.159	0.086
Male		0.325*	0.208		0.351*	0.020		0.676***	0.890***
STEM × male			0.212			0.872***			−0.442
R^2	0.364	0.450	0.473	0.286	0.391	0.555	0.021	0.385	0.426

Note: $N = 40 - 41$, *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

	Seeing the relevance of STEM			Progress in understanding STEM		
	model 1	model 2	model 3	model 1	model 2	model 3
STEM	0.362*	0.359*	−0.120	0.354*	0.220	−0.039
Male		0.008	−0.286		0.346*	0.159
STEM × male			0.733*			0.423
R^2	0.131	0.131	0.242	0.125	0.227	0.266

Note: $N = 39 - 42$, *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

4. – Results

4·1. *Cognitive test on mechanics.* – The cognitive test in the STEM class exhibited some clear results, as can be seen in the scores of the evaluated items in table III. They performed rather well at interpreting graphs, on average the right or wrong quotes were assessed correctly by 60.0 percent of the pupils.

In general, the pupils showed some flexibility in switching between different forms of representation, more specifically graphs and tables (63.0 percent). Formulas and non-linear graphs on the other hand seemed to be more difficult for them to deal with or to analyse. Finally, we discovered that the pupils were not able to use the concepts they learned in the integrated context of math and physics, in a pure math context: only 16.0 percent of the pupils managed to construct a graph of a pure math function (table III).

4·2. *Survey on the attitude towards STEM.* – The results in table IV indicate that enrolment in a STEM class is positively related to four of five indexes measuring attitudes towards STEM: general interest in STEM, job expectations, relevance of STEM, and progress in understanding (model 1). Although there is a clear difference in gender distribution between the STEM class and the non-STEM class, the relationship between enrolment in the STEM class and pupils' attitudes remains statistically significant even when controlling for gender (model 2).

Gender too is significantly related to four of five indexes measuring attitudes towards STEM: general interest in STEM, job expectations, belief in gender differences, and progress in understanding (model 1). Boys seem to be interested in STEM more than girls, believe more than girls to make progress in understanding STEM issues over the year, and believe more often than girls that boys are better in STEM than girls (model 2).

In case of job expectations and relevance of STEM, the interaction term between enrolment in STEM and gender (model 3), is statistically significant. Boys and girls in the non-STEM class showed equal interest in STEM jobs. In contrast, there is a large gender gap in the STEM class: girls in the STEM class showed less interest in STEM jobs than any pupil of the non-STEM class, whereas boys in the STEM class showed more interest in STEM jobs than all other pupils. Likewise, a similar gap exists in the STEM class between boys and girls with regard to seeing the relevance of STEM. This gender gap is much larger than in the non-STEM class.

5. – Discussion and conclusion

In this paper we discussed an integrated STEM course in a Flemish secondary school, newly developed to show the relevance of STEM for real life, by introducing the STEM disciplines in an integrated way. Two post-test designs (one with a non-equivalent control group) were used to evaluate the potential effect of integrated STEM education. Although we need to be careful about making causal inferences, we observed that some interesting results emerged.

Pupils who were enrolled in the STEM class can switch between different kinds of represen tations (graph to table or to real life), construct and deduct simple graphs, the first step in learning how to make abstraction and models. However, manipulating mathematical formulas is still perceived as a difficult topic that should anyhow be approached by an integrated as well as a non-integrated way. Therefore, the new batch of STEM pupils will receive some required minimal initial training in *pure math context*, *prior to the integration* in a scientific context.

In general, STEM pupils show a more positive attitude towards STEM than pupils enrolled in a non-STEM class, even taken into account the fact that less girls are enrolled in the STEM class than in the non-STEM class. Although we were not able to administer a pre-test and thus cannot make any causal inferences, we do find it remarkable that, regarding job expectations and relevance perception, the gender gap in the STEM class is larger than in the non-STEM class, indicating that at least the girls' interest and perceptions likely did not improve much after being exposed to integrated STEM education. This is important to keep in mind when implementing integrated STEM education. Therefore, the learning path of Mechanics will be embedded more in different contexts, *e.g.* biology (Klein and Sherwood, 2005).

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