This is an Accepted Manuscript of an article published by Taylor & Francis Group in ***Bioscience education*** *on June 2012, available online:*
http://www.tandfonline.com/doi/full/10.11120/beej.2012.19000006

Title: Mathematical skills in undergraduate students. A ten-year survey of a Plant Physiology course.

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Type of article: Research article.

Keywords: mathematical literacy, numeracy, Plant Physiology, self-efficacy, tertiary education.

Number of words: 3924

Running title: Mathematical skills in undergraduates.

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Abstract

In the health and life sciences, as well as in other scientific disciplines, problem solving depends on mathematical skills. However, significant deficiencies are commonly found in this regard in undergraduate students. In an attempt to understand the underlying causes and to improve students' performance, this paper reports a ten-year survey (2000-2010) on mathematical skills of undergraduate Spanish students enrolled in a Plant Physiology course, based on data from tests performed throughout this time period. The results show that the percentage of correct answers decreases for questions requiring some mathematical skills, particularly those needing some calculations. Interestingly, percentages of failure are similar for both types of questions. These results suggest not only the existence of weaknesses in students' mathematical competency but also a lack of self-efficacy. Additionally, although mathematical questions represented only about 14 % of all the questions and did not show higher discrimination coefficients (0.27 versus 0.29), they demonstrated to be a good predictor of the students final grade.

Introduction

University students should develop competences in a wide range of cognitive skills and thus, acquire “expert” knowledge in their field (Anderson and Schönborn, 2008) which will enable them to solve new problems. In the biological sciences as in other scientific disciplines, resolution of some of these problems depends on mathematical skills. However, different studies report on mathematical deficiencies in undergraduate students at the beginning of higher education (González, 2000; Mulhern and Wylie, 2005; Orozco-Moret and Díaz, 2009; Pablo-Romero et al., 2009). In the same sense, Gross (2000) indicated that a lot of teachers from different countries complain about students’ poor comprehension of basic quantitative concepts. This includes students of scientific disciplines such as Medicine (Sheridan and Pignone, 2002), Nursing (Eastwood et al., 2011) or Biosciences (Tariq, 2002). In fact, the idea that Biology has often been considered the ideal career for students inclined to science but mathematically challenged has even been pointed out in an editorial note in the "Points of view" section, which appeared in the journal Cell Biology Education (2004; www.ncbi.nlm.nih.gov/pmc/articles/PMC437648). According to LeBard et al. (2009), considering the previous curricula, students must have acquired enough mathematical background when entering university. But despite of this, they still show numerical weaknesses. In their analysis of the underlying causes, these authors indicate that students' struggle with maths is related to two factors: "lack of relevance, which reduces the student’s willingness to engage with the challenging aspects of the maths and with difficulties in transforming their mathematical training into a form that allows them to use it effectively".

Additionally, weakness in mathematical skills not only influences the students' scientific learning but it may also represent a major drag for their employability. Among other requirements, employers seek competent employees in relation to maths literacy (Tariq, 2004). The term "maths literacy" was introduced to indicate the ability to apply mathematical concepts to the work context (Hoyles et al., 2002). Maths literacy, then, includes basic numeracy, but implies further cognitive skills, and can be easily generalised to any other context, including science.

On the other hand, self-efficacy, that is, the confidence in one's ability to successfully carry out a task, has proved to be an important factor in the learning of Biology and other sciences, as well as in problem solving (Erlinger and Dunning, 2003; Lawson et al., 2007; Taasoobshirazi and Glynn, 2009; Zusho et al., 2003). Further, Bresó et al. (2010) showed that self-efficacy-based interventions can enhance students' performance. In a study conducted on the results of the Programme for International Students Assessment for 2003 (PISA 2003), which assesses high school students from the OECD countries, Schulz (2005) demonstrated the existence of a significant positive correlation between self-efficacy and both students' math performance and expectations of carrying out an academic tertiary qualification. In contrast, other studies report that the students' degree of confidence does not correlate with final results (Bowers et al., 2005).

The current study analyses the results obtained over ten academic years by undergraduate students enrolled in a Plant Physiology course, in relation to the resolution of questions that require primarily the use of maths literacy. In these questions, the numeracy needed is really simple, considering the students' background. In Spain, Biology students have taken the branch of Health and Life Sciences during high school, in which mathematics is compulsory during the first year and optional in the second one, the year prior to university entry. Subsequently, they have to attend courses in Mathematics and Biostatistics, as well as other subjects, like Physics or Chemistry, which also use mathematics as a tool. Until 2010 the degree in Biology in the Spanish University took 5 years to complete. In the University of Valencia, Plant Physiology was a compulsory subject of the 3rd year of the Biology degree.

The aim of this work is to understand the difficulties that students encounter in the resolution of Plant Physiology problems that require mathematical skills, in order to be able to help them to improve their academic performance. Quantification of mathematical skills has been made by scrutinising answers to questions included in the Plant Physiology exams during the last ten years. Thus, this work reports on maths literacy of undergraduate students and in this sense it differs from other studies, mainly focused on numeracy skills, as they use pure mathematical tests to quantify students' mathematical abilities. Additionally, we also report on the effect of a group intervention in the students' self-efficacy.

Methods

The survey covers the results obtained from multiple choice tests used for evaluation in groups of Plant Physiology along the academic years 2000/01 to 2009/10, with an average of 108 students per year. The number of tests per course ranged from 3 (period 2000-2004) to 4 (2004-2010), as in 2004/05 we added another preliminary exam. Each exam consisted of 20 to 45 items, depending on whether it was a preliminary or a final exam, therefore including only part or the whole subject content. This number is lower than usual in multiple-choice tests, despite tests with higher number of items being generally more reliable (Tarrant and Ware, 2008). However, since our tests were composed of rapid answer questions together with others requiring some time for resolving, including some numerical calculations, we decreased the number of items in order to reduce the time which would otherwise be necessary to complete the test and which might have affected students' performance. The exams were not time limited and 80 % of the students finished the test within 2 h.

Despite the low number of items, only a few exams showed a reliability coefficient (Kuder-Richardson 20, KR_{20}) lower than 0.5, considered sufficient for drawing meaningful conclusions (Downing, 2002), and these were not included in the study. The mean reliability of the tests used, calculated through the PASW Statistics program, version 17.0.3, was $KR_{20} = 0.67 \pm 0.10$. Difficulty indices showed a mean value of 0.49 ± 0.23 and the mean discrimination coefficient was 0.29 ± 0.23. The items included in each test were agreed between three faculty members, all of them long-experienced teachers of the

Plant Physiology course. Each item was selected when the three teachers considered that it matched at least one of the objectives of the course. Validity of the tests, therefore, fulfilled the usual standards (Anderson and Rogan, 2010; Downing, 2003).

We classified all questions in this set of exams and selected those requiring mathematical skills, yielding a total of 153 questions, that is, 14.2% of all the proposed items. Within the selected questions 38% required to perform some calculations, 47% consisted in the interpretation of graphics, drawing conclusions or inferring possible consequences from them, and in the remaining 15% the stimulus format was similar, but data were presented numerically in tables. The study covers a total of 7961 responses (Table 1). Though items classified as "calculation" required, in general, more numeracy skills, they were also presented into the context of the Plant Physiology subject and, in common with the other types of questions, are therefore considered indicative of students' maths literacy. Statistically significant differences between results obtained for the different types of questions were established by two-tailed z-tests for proportions with the PASW Statistics Program (v.19.0). Correlation analysis was performed with the VassartStats program and differences among slopes were established by Ancova tests, performed with the same program.

Results and discussion

Examples of the types of mathematical questions included in the tests are shown in Box 1. Question A was included in two different years, resulting in very low percentages of correct answers in both exams (17 and 13%) despite its simplicity, as its resolution depends basically on numeracy skills. The failure rate was 25 and 33%, while 59 and 53% of students did not respond. With respect to resolution of question B, the students should know the relevant concepts and understand the graph, but numerically only needs a subtraction using the data extracted from the graph. In this case, there was a similar percentage of error as for question A (31%). For question C, with much numerical information but which did not require any calculation, the number of errors was much lower (5%) though the percentage of blank answers was high (42%).

Global results of the tests surveyed (Figure 1) show that the percentage of correct answers for questions requiring mathematical skills is 16% lower than for the corresponding non-mathematical questions. This result indicates that there are deficiencies in students' mathematical competencies, and agrees with other reports for science students (Eastwood et al., 2011; Gross, 2000; Sheridan and Pignone, 2002; Tariq, 2004). However, it is interesting to note that the failure rate for both types of questions is similar, around 30 %, so the difference lies in the rate of questions left unanswered (31% of mathematical questions compared to 17% of non-mathematical ones).

When the three types of mathematical questions (calculations, graphs and tables) are compared, results show that the percentage of correct answers is low for all of them, as they hardly reach 40%. As shown in Figure 2, questions requiring calculations significantly differ from the other types of questions, not only with respect to correct answers but also to failures and blank answers. The issues of calculation give lower failure rates, but the highest number of unanswered questions. It can be assumed that, somehow, the blank responses are reflecting not only knowledge deficiencies but also, and in our view significantly, the perception that students themselves have about their ability to answer the question. This could explain why simple questions such as those in Box 1 result in such a high percentage on blank answers.

Questions relating to the interpretation of graphs are more visual and apparently easier to grasp (Arcavi, 2003; Duval, 2000; Presmeg, 2006), thus showing the highest response rate (76%). However, they also show the highest percentage of errors (35%). According to our results, students' achievement seems strongly influenced by lack of confidence in their own abilities. Our perception is that many good students that worry about poor performance in relation to the time devoted to the subject, do better when we can convince them during tutorial sessions of their ability to master the subject.

The hypothesis of a lack of students self-efficacy is supported by the evidence given by the changes in the rates of participation in final exams during the period studied. In general, the participation rate in relation to the number of students enrolling on the course is low, always below 75% (Figure 3A), and decreased progressively during the first academic years. But it increased by 20 % in 2004/05, coinciding with the introduction of an additional preliminary test that allowed them to reduce the contents for the final exams. If the low participation rates were due to the perception of real knowledge deficiencies, a higher participation would have led to a decrease in the rate of students getting a pass degree in relation to previous academic years. However, the number of successful students increased with higher participation indicating an enhancement in student's confidence in their ability to pass the subject, that is, in self-efficacy. In these academic years, the correlation existing between number of successful students and number of students taking the exams was similar to the courses with fewer preliminary tests, and no significant differences were detected between both slopes (Figure 3B).

Moreover, the average scores obtained for the mathematical questions along the courses varied in parallel with the percentage of successful students (Figure 4). Thus, it can be considered a good predictor of final results for this subject, despite the fact that mathematical questions are only about 14% of total issues and therefore of the final score. A further correlation analysis considering math scores for each student shows that the relationship with final grades is maintained at the individual level (data not shown). Mulhern and Wylie (2004, 2005) working with students of Psychology reached a similar conclusion. Additionally, since discrimination coefficients for mathematical items, both overall and for each type of questions considered, are very similar to the mean discrimination index for all questions (0.24-0.28 versus 0.29), it seems that having mathematical skills is related to good performance in scientific disciplines, such as Plant Physiology, and not only in maths. This is reflected in answers to both, numerical and non-numerical questions and is congruent with results reported by Sadler and Tai (2007), who showed that academic results obtained by science students are related with the previous number of years of maths instruction.

Our students know and understand the criteria by which they will be evaluated, since they are explained in detail at the beginning of the course ("transparency issue", according to Anderson and Rogan, 2010). To improve students' performance, we implemented this aspect with a new activity initiated in the 2006-07 academic year. Thus, in order to become familiar with the test format and practise the different competencies they should acquire and demonstrate at the final exams, we prepared and put at the disposal of the students a series of exercises, with issues similar to those of the examinations, of both mathematical and non mathematical type. Furthermore, to strengthen the quantitative aspect of Plant Physiology, a practical session was dedicated to solving mathematical questions and the students were provided with an additional questionnaire. So far, its resolution is strongly recommended and dealt with in tutorials of voluntary attendance. This initiative, although it appears to have been positive in other respects, has not increased, however, self-efficacy and in the last years the participation rate has again begun to decline (Figure 3), so in future courses we study other ways to encourage the students to perform these additional tasks. Among other activities, a data base of on-line questionnaires is being prepared in collaboration with faculty members from other scientific disciplines (Martínez-Tomás et al., 2011).

In conclusion, the data from this survey focusing on mathematical skills of undergraduate students of a scientific subject, demonstrate the existence of significant deficiencies in maths literacy that are, at least in part, due to lack of self-efficacy. Mathematics is an essential tool for any scientific subject and quantitative approaches are crucial to understand and solve problems in all areas of the health and life sciences (Bialek and Botstein, 2004; Gross, 2000). It is therefore essential to strengthen mathematical skills in undergraduate students and especially their ability to apply all previously acquired knowledge throughout their education, thereby reducing their "perception that math is only needed for math courses" (Gross et al., 2000) and making them feel more self-confident about using them. To this end, different strategies have been proposed. Thus, Phoenix (1999) suggests the introduction of specific modules to develop mathematical skills, whilst Bialek and Botstein (2004) propose a unified introductory science curriculum including mathematics and quantitative thinking. Gross (2000) supports the inclusion of quantitative approaches throughout the rest of the subjects instead of isolating mathematics in specific quantitative courses, and also Labov et al. (2010) indicate that science education must be an integrated intent of interdisciplinarity. Though we agree with Tariq (2004) in that there is not a single strategy that may serve in all cases, in our opinion the curriculum changes should be less in the sense of adding more subjects of mathematics, but rather in increasing their practical use in the various experimental disciplines that use them as a tool.

Acknowledgements

We thank Mrs. Eunice Martin for correcting the English.

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Table 1. Total number of questions and answers to the exams from the period under study (2000-2010) and number of questions requiring mathematical skills. Numbers in parenthesis correspond to percentage of total questions.

	Type of questions			
	Non-mathematical	Mathematical		
		Calculations	Graphs	Tables
Number of questions	925 (85.8 %)	58 (5.4 %)	72 (6.7 %)	23 (2.1 %)
Number of answers	37 981	3209	3762	990

Box 1

Examples of types of questions and mathematical skills required for resolution.

A. Calculation

To perform a lab experiment 250 mL of a solution of water potential = -0.8 MPa are required. How many grams of NaCl must be taken in order to prepare it?
(Data: Ψ_s = -mRiT; Pm NaCl = 58.45; R = 8.3 x 10 $^{-3}$ MPa L $^{-1}$ ºK $^{-1}$ mol $^{-1}$; T = 25 ºC).

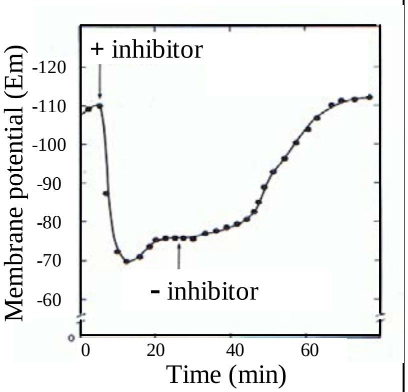
a. 2.4
b. 0.24
c. 4.7
d. 0.47

Number of responses: 147 Correct answers: 15% Failures: 28% Blanks: 57%

B. Graphics

The figure shows the changes in membrane potential (Em), in mV, of cortical cells of a plant, recorded during the addition and removal of a metabolic inhibitor to the solution in which it is submerged. Indicate the value of the potential generated by active forces (proton motive force, Δ p):

a. – 110 mV
b. – 75 mV
c. – 35 mV
d. 0 mV



Number of responses: 52 Correct answers: 34% Failures: 31% Blanks: 35%

(Figure taken from Higinbotham et al. 1970. J Membrane Biol. 3: 210-222).

C. Tables

Seeds of a dock (*Rumex* sp.) were germinated and the seedlings grown for 35 days under bright lights, which (it was predicted) would convert 70 % of the phytochrome present to the Pfr form (treatment A). Some seedlings were then transferred to two qualities of dim lighting (the intensity of each being 40 % of the original), one of which was predicted to give 40 % Pfr (treatment B) and the other 70 % (treatment C). Leaf area and petiole length were estimated after six days. The results are shown in the table.

Treatment	Light intensity	% Pfr	Leaf area (cm^2)	Petiole length (cm)
A	100	70	158	3.89
B	40	40	208	5.53
C	40	70	209	4.02

According to the data, variations in leaf area and petiole length appear under the control of:

a. light quality (% of Pfr)
b. the amount of light (% light intensity)
c. light quality (% Pfr) in the case of the petiole and amount (% light intensity) in the leaf area
d. light quality (% Pfr) in the case of the leaf area and amount (% light intensity) in the petiole length

Number of responses: 75 Correct answers: 53% Failures: 5% Blanks: 42%

(Question taken and adapted from Ridge I, 1990. Plant Physiology. The Open University. Hodder & Stoughton).

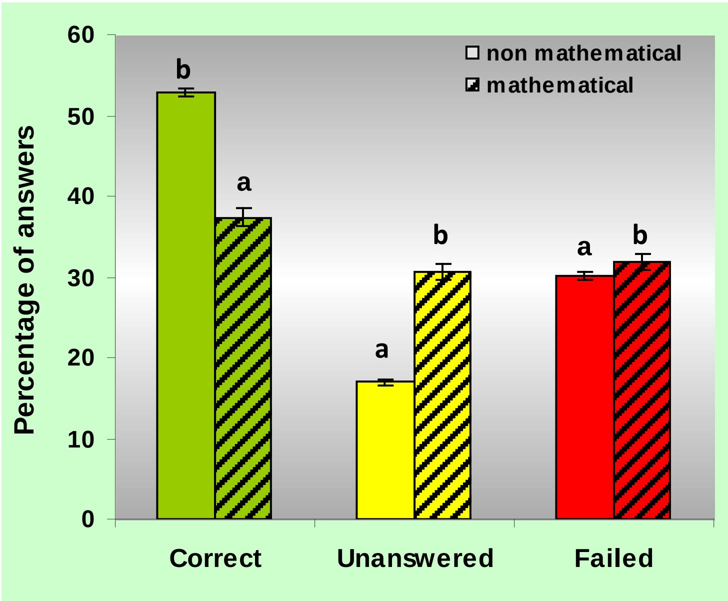


Figure 1. Percentage of answers obtained for questions requiring or not mathematical skills for the period studied (2000-2010). Within each type of response, different letters indicate significant differences, according to z-tests ($p < 0.001$). 95 % confidence intervals are shown as vertical bars.

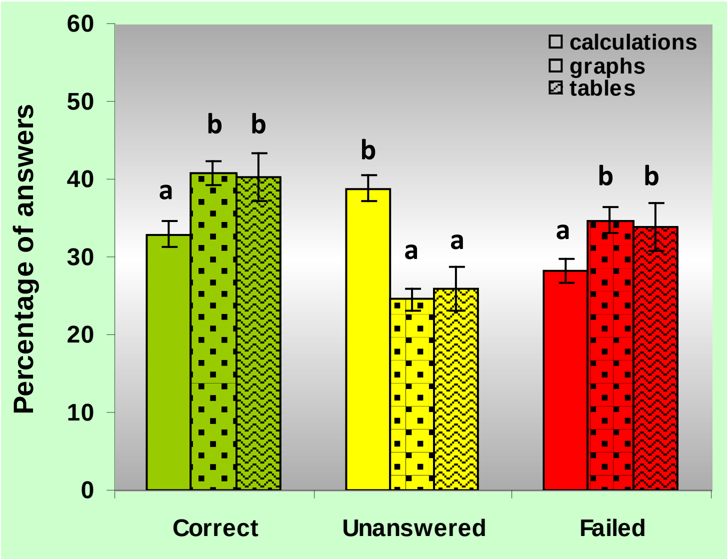


Figure 2. Percentage of answers obtained for the different types of questions requiring mathematical skills for the period studied (2000-2010). Within each type of response, different letters indicate significant differences, according to z-tests ($p < 0.001$). 95 % confidence intervals are shown as vertical bars.

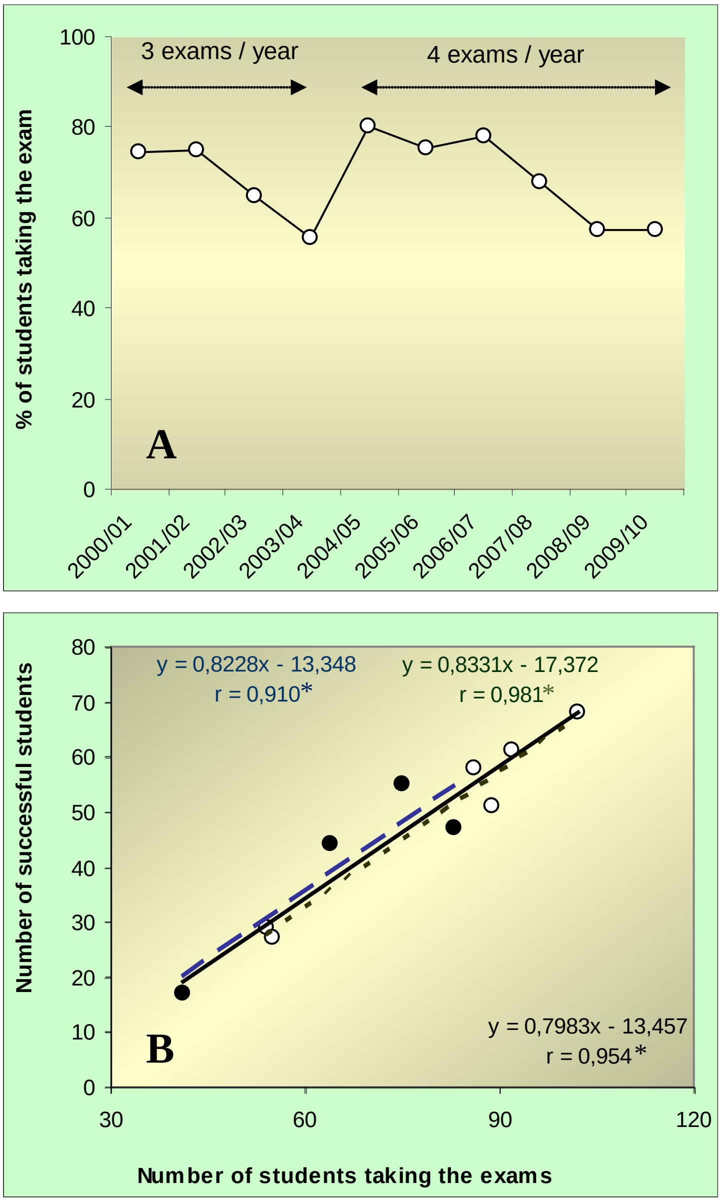


Figure 3. Percentage of students taking the final exams along the period studied (A) and correlation between number of students taking the final exams and number of successful students per year (B). Closed and open circles correspond to academic courses with 3 and 4 exams per year, respectively. The asterisk indicates statistically significant correlation ($p < 0.01$). No statistically significant differences between slopes were detected ($p < 0.05$)

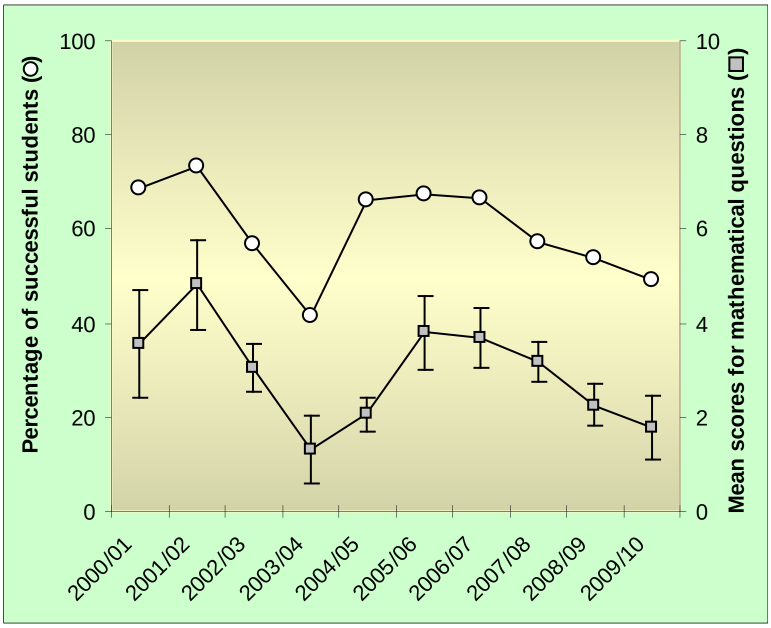


Figure 4. Time-course variations of percentage of successful students per year (circles) and mean scores obtained by all students for questions requiring mathematical skills (squares). Vertical bars indicate SD.