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ORIGINAL ARTICLE

Physics-Mathematics Associations: Evidence from TIMSS Student Achievements

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ABSTRACT

The study aimed to determine the extent of associations of physics, mathematics, and between physics and mathematics based on the results of the 2007, 2011, and 2015 Trends in Mathematics and Science Survey achievement tests. Utilizing educational data mining and correlational data analysis (significance set at $\alpha = 0.05$), this study's findings revealed that there was a significant positive correlation between elementary physics and secondary physics ($r = 0.821$, $\rho = 0.045$), between elementary mathematics and secondary mathematics ($r = 0.914$, $\rho = 0.011$), between elementary physics and elementary mathematics ($r = 0.914$, $\rho = 0.011$), and between secondary physics and secondary mathematics ($r = 0.891$, $\rho = 0.017$). With these findings, the study concluded that physics and mathematics in elementary and high school are significantly associated that physics is not significantly associated with previous-level mathematics and that advanced courses in physics and mathematics are not associated with the secondary counterparts. Furthermore, implications toward physics education in the Philippines are formulated.

KEY WORDS: mathematics achievement; physics achievement, physics-mathematics associations; trends in mathematics and science survey

INTRODUCTION

Physics is the study of the world around us. At its strictest sense, it deals with the interactions of matter and energy such as motion, light, and electricity. It studies physical phenomena, ranging from movements of the parts of the body, engine mechanisms of vehicles and flow of electricity in appliances to utilization of the sun for energy, construction of very minute electronic components for mobile phones and flight of rockets to outer space (Chen et al., 2000; Simpson, 2019). In this context, physics is a very significant field in science, and as such, learning its concepts and skills are needed in a highly modernized 21st century society (Kikkawa et al., 1996; Redish, 2000; Raspanti, 2008).

Since its value in the society is essential, physics education has become a vital component of science education in the 21st century. As a component of science education, physics provides a means of promoting a strong link between science and technology, thereby leading to producing innovative and creative citizens of the country (Osborne and Dillon, 2008; Jolly, 2009; Department of Education, 2016). In addition, physics does not only link science to technology but also links the fields within the sciences. In fact, many studies (e.g. Perkins et al., 2007; Crook et al., 2015; Visser, 2017) have been conducted to determine the extent of the link or relationship between physics to other fields in science education through investigating variables, which could describe such relationships. Perkins et al. (2007) saw that physics and chemistry were viewed as connected fields, which could provide principles essential for solving a variety of problems in the society. Crook et al. (2015) found out that physics teaching involved more higher-order activities and higher utilization of technology in the classroom than biology teaching, thereby suggesting the technological characteristic of former to the latter. Importantly for this paper, Visser (2017) argued how physics creates the questions, which need mathematics to develop the answers.

Two studies have investigated the relationship between physics and mathematics using data set from trends in mathematics and science survey (TIMSS) results. Nilden et al. (2013) used trend date to explore the importance of mathematical competencies in physics and found out that such competencies could be related to physics performance. Wang (2005) determined the relationship between mathematics and science achievements and revealed that there was a moderate correlation between the two sets of achievements. To further the studies concerning the relationship of physics to other fields, the study aimed to determine the relationship between physics and mathematics through the use of achievement data set as provided by TIMSS results. Specifically, this paper sought to determine the relationship between lower and higher physics courses, as well as between physics and mathematics courses from elementary and secondary to advanced levels. The paper revolved around the assumption that mathematical concepts and skills were essential components of better physics learning, thus leading to higher achievement.

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CONCEPTUAL FRAMEWORK

The conceptual framework of the study is presented below:

As presented in Figure 1, physics learning is a process that involves the acquisition of knowledge and skills in physics, understanding of concepts and principles in the physical world, and the application of mathematical skills and process in physical contexts. Application of mathematics to the knowledge acquisition and conceptual understanding of physical principles creates the physics-mathematics interface where physics learning increases in complexity as learners move from one level to another. The extent of the association in the interface in the elementary, secondary, and advanced levels could determine the physics achievement of learners.

METHODS

This study used a data mining procedure called educational data mining (EDM). This is an emerging research design that can capture and create trends in educational settings coming from big data sets such as TIMSS (Kumar and Vijayalakshimi, 2011). In this study, EDM on the data bank from three sets of TIMSS results was done to determine the relationships between physics and mathematics, as evidenced from the results of six countries: Italy, Norway, Russian Federation, Slovenia, Sweden, and United States. These countries were selected as their students participated in 2007 when they took the assessment as Grade 4 students, in 2011 when in Grade 8, and then in 2015 when they took advanced courses. The variables included in the analysis were elementary physics and elementary mathematics achievement, that is, physical science and mathematics achievements of Grade 4 in 2007 (Mullis et al., 2008; Martin et al., 2008), secondary physics and secondary mathematics, that is, physics and mathematics achievements of Grade 8 in 2011 (Martin et al., 2012; Mullis et al., 2012), and advanced physics and advanced mathematics, that is, advanced course achievements in 2015 (Mullis et al., 2016a; 2016b).

To determine whether there was a significant association involving physics and mathematics achievements of students, the Pearson r correlation analysis was used by the study. Significant association is set at $\alpha = 0.05$ for educational studies (Andrade, 2019).

RESULTS AND DISCUSSIONS

Profile of the Participating Countries

The TIMSS reference books highlight four variables that describe the profile of the selected countries in the study. These are years of formal schooling, average age at time of testing (Table 1), percentage of male/female student participants (Table 2), and human development index (HDI) (Table 3).

Based on Table 1, all the participating countries had 4 and 8 years of formal schooling for their students when they took the Grade 4 and Grade 8 tests, respectively. However, countries have different number of schooling years – ranging from 11 to 13 years – for their students to take the advanced tests. They took the advanced tests in their final year of secondary education; thus, they took the tests in different grade levels. In terms of age, the test takers in Grade 4 (9.8–10.8 years old) had comparable ages among the countries as well as those in Grade 8 (13.7–14.8 years old) and in the advanced levels (17.7–18.9 years old). Participants from Italy, Norway, and Slovenia were the youngest in Grade 4 and Grade 8, while those from the Russian Federation were the youngest in the advanced levels.

As seen in Table 2, there were comparable numbers of males and females who took the Grade 4 and Grade 8 tests in 2007 and 2011, respectively. For advanced tests in 2015, there were differences in the number of male and female test takers among the countries, with a greater number of

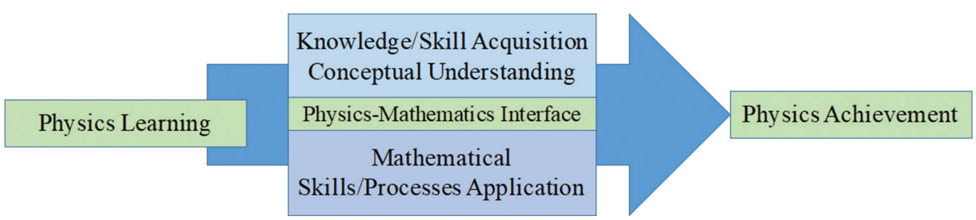

Figure 1: Conceptual framework

Table 1: Years of formal schooling and average age at time of testing

Country	Years of formal schooling			Average age at time of testing		
	Grade 4	Grade 8	Advanced	Grade 4	Grade 8	Advanced
Italy	4	8	13	9.8	13.8	18.9
Norway	4	8	13	9.8	13.7	18.8
Russian Federation	4	8	11	10.8	14.7	17.7
Slovenia	4	8	13	9.8	13.9	18.8
Sweden	4	8	12	10.8	14.8	18.8
United States	4	8	12	10.3	14.2	18.1

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male participants than females. This may mean that in these countries, males were more engaged in special programs in physics than females.

Table 3 presents the HDI of the selected countries in the study. Almost all the countries had a very high HDI since 2007, with only the Russian Federation has High HDI in both 2011 and 2015. This connotes higher educational level in these countries. These countries prioritized education as a major component of their students' well-being. It would then be expected that these countries would provide more optimum resources to attain maximum learning, including in the fields of physics and mathematics.

Student Achievements of Participating Countries in Physics and Mathematics

The student achievements of the participating countries in physics and mathematics are shown in Figures 2 and 3, respectively.

As noted in Figure 2, the students in five of the six countries had physical science achievements above the TIMSS

Table 2: Percentage of male/female participants in TIMSS achievement tests

Country	2007		2011		2015	
	% Male	% Female	% Male	% Female	% Male	% Female
Italy	51	49	51	49	54	46
Norway	50	50	51	49	71	29
Russian Federation	50	50	51	49	58	42
Slovenia	51	49	51	49	70	30
Sweden	50	50	52	48	59	41
United States	49	51	49	51	61	39

TIMSS: Trends in mathematics and science survey

Table 3: HDI of the participating countries

Country	2007		2011		2015	
	HDI	Description[a]	HDI	Description[a]	HDI	Description[a]
Italy	0.941	Very high	0.874	Very high	0.873	Very high
Norway	0.968	Very high	0.943	Very high	0.944	Very high
Russian Federation	0.813	Very high	0.755	High	0.798	High
Slovenia	0.917	Very high	0.884	Very high	0.880	Very high
Sweden	0.956	Very high	0.904	Very high	0.907	Very high
United States	0.951	Very high	0.910	Very high	0.915	Very high

[a]0.800–1.000 (Very high), 0.700–0.799 (High), 0.550–0.699 (Medium), 0.350-0.549 (Low). HDI: Human development index

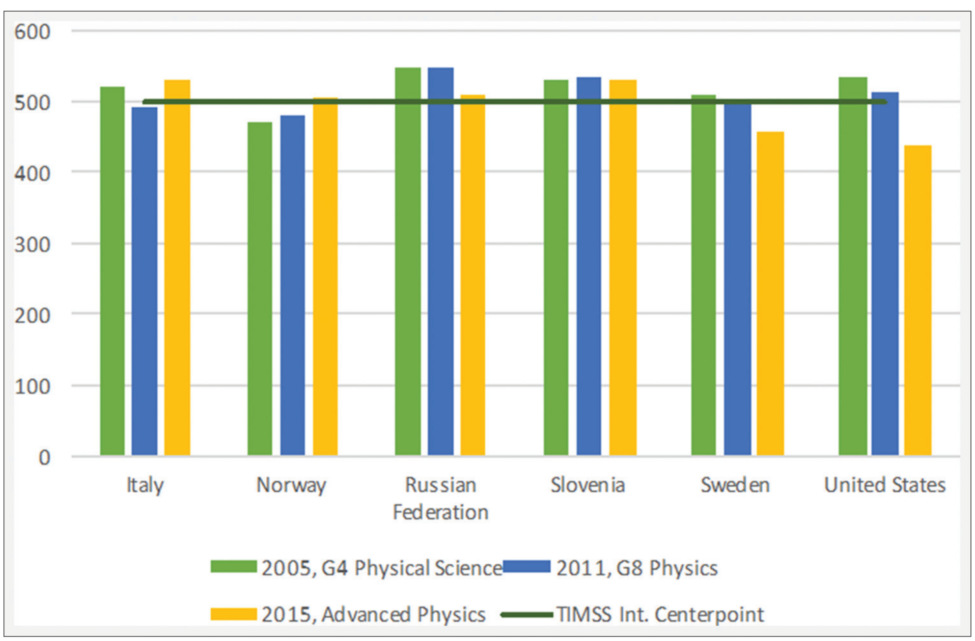

Figure 2: Physics achievement of selected countries

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international center point; this means that these countries had higher achievements than the overall achievement distribution. All but Italy and Norway had physics achievements higher than TIMSS center point, while all but Sweden and United States had advanced physics achievements higher than that center point. Only the Russian Federation and Slovenia had achievements higher than the center point for all illustrated physics achievements.

Based on Figure 3, all but Norway had Grade 4 (G4) mathematics achievements higher than overall achievement distribution. Russian Federation, Slovenia, and United States had Grade 8 (G8) math achievements greater than the overall distribution. None of the countries had advanced math achievements higher than such distribution.

Associations in Student Achievements

The association within and between physics and mathematics in student achievement is statistically summarized in Figure 4.

Physics Associations

Elementary physics and secondary physics

As noted in Figure 4, G4 physical science and G8 physics achievements had positive and significant correlations with each other. This means that elementary physics and secondary physics are significantly associated with one another, indicating that knowledge about basic phenomena contributed to the achievement of students in physics in high school. Elementary physical concepts and principles activate the curious and inquisitive nature of the students, which serve as the foundation for future specialized science, physics for instance, in the secondary level (Cook, 2018). These elementary concepts and processes encourage and engage students in science they need to know and be able to do in the next step of the educational ladder (Butler, 2009). The association between elementary and secondary physics shows that vertical articulation is a vital characteristic of the science curriculum. Vertical articulation reflects the logic and consistency in teaching physics subjects, where fundamental concepts on motion, force, and energy are taught first, then the intermediate concepts on projectile, free-fall and power, and ultimately electromagnetism, electronics, and relativity (Case and Zucker, 2005).

Secondary physics and advanced physics

Figure 4 highlights that G8 physics and advanced physics achievements had a positive yet insignificant correlation, indicating that there was no significant association between secondary physics and advanced physics. This suggests that physics concepts taught in high school inadequately contributed to the learning of students in advanced physics. Fundamental lack of alignment between secondary and advanced course curricula is seen to lead to lack of expectations and support for students as they progress to the next higher level (Ciciora, 2010). This association of physics subjects in the secondary and advanced levels suggests that an absence of coherence and articulation in the curriculum provides barriers in the teaching and learning process since teachers (senior high school and college) consider their students to have learned those in the previous levels (Abbott, 2001).

Mathematics Associations

Elementary mathematics and secondary mathematics

G4 mathematics and G8 mathematics had positive and significant correlations, indicating that there was a significant association between elementary mathematics and secondary mathematics. This means that the mathematical concepts and skills in the elementary level are contributory to the achievement of students in secondary mathematics. Mathematical building blocks such as numbers, place value system, whole number operations, fractions and decimals,

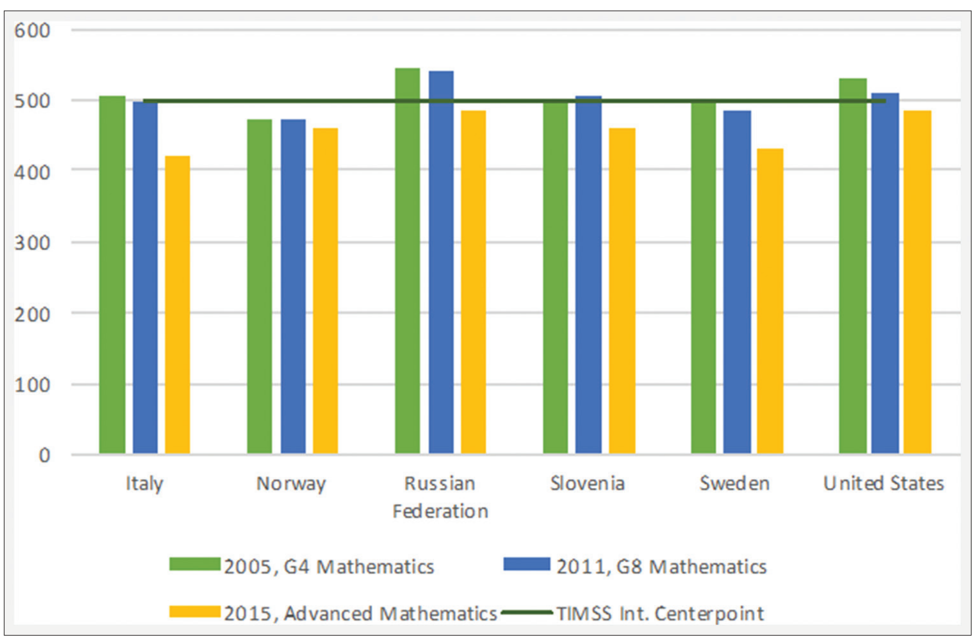

Figure 3: Mathematics achievements of selected countries

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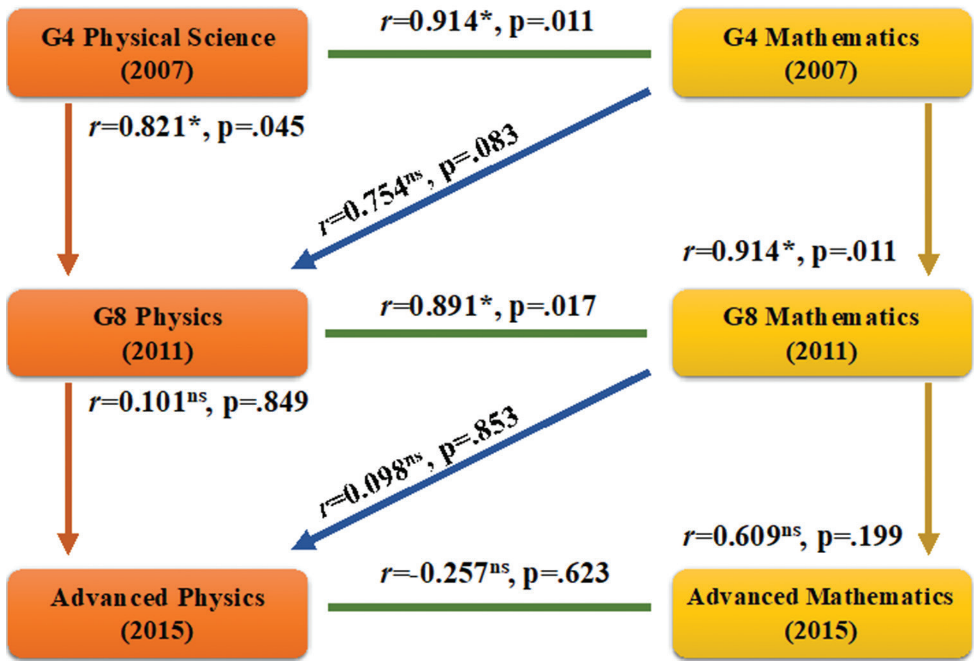

Figure 4: Statistical associations between physics and mathematics

and problem solving are critical to learning mathematics in high school and in higher levels of study (Wilson, 2009). Like the physics association between elementary and secondary levels, mathematics association between the same levels shows the importance of vertical articulation in mathematics. Such articulation denotes that mathematics has a conceptual structure, as there is a development of mathematical ideas as concepts become complex. This, in turn, needs the underlying concepts (i.e., foundational math) to understand the complex ones (Suh and Seshaiyer, 2015).

Secondary mathematics and advanced mathematics

Based on Figure 4, G8 mathematics and advanced mathematics had a positive yet insignificant correlation with one another. This means that there was no significant associated between the student achievements in secondary mathematics and advanced mathematics. This suggests that high school mathematical concepts and skills are inadequate in understanding the higher-level Maths, as curriculum in high school and the advanced levels are unrelated (Dupuis et al., 2012). This means that some pre-requisite concepts and skills are not taken up or tackled in the previous high school Maths, showing a mismatch in the articulation between secondary and advanced levels (Madison, 2003).

Physics-Mathematics Associations

Elementary physics and elementary mathematics

G4 physical science and G4 mathematics had a positive and significant relationship with one another. This means that elementary physics and elementary mathematics are significantly associated, indicating that the basic mathematical operations taught in the elementary led to the understanding of the basic concepts, thereby contributing to the achievements of students in elementary physics. This association may be attributed to the fact that mathematics is needed to stimulate and support the process skills of students in the primary levels to understand the essential concepts of the physical world such as the basic quantitative tenets of motion, force, and energy (Elstgeest et al., 1993). In the same manner, elementary physics just like other sciences provides the representation of the basic principles of the physical world, and eventually the reality through the use of scientific investigations, which evoke mathematical activity and improve mathematics (McNamee, 2010). The fusion of these functions of physics and mathematics in the elementary level contributed to the creation of models of the physical world where neophyte learners use to understand further the world where they live in (Elstgeest et al., 1993; van den Berg et al., 2006).

Elementary mathematics and secondary physics

G4 mathematics and G8 physics had a positive yet insignificant correlation with one another, indicating that there was no significant association that existed between student achievements in elementary mathematics and secondary physics. While foundational mathematics helped in elementary physics learning, such foundational concepts and skills are not enough to contribute to the learning of physics in the secondary level. More complex concepts and skills than those in the elementary level are needed in high school physics to complement with the quantitative aspects of the latter. Poor or inadequate mathematical concepts and skills become a problem in physics teaching and learning (Reddy and Panacharoensawad, 2017).

Secondary physics and secondary mathematics

G8 physics and G8 mathematics were found to be positively and significantly correlated, indicating that there was a significant

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association that existed between secondary physics and secondary mathematics. This means that the mathematical concepts and problem solving skills in high school are in line with the concepts and skills needed for secondary physics understanding. Mathematical skills (i.e., pre-instruction Algebra) are seen to be associated with the students' facility to acquire physics conceptual knowledge in high school (Meltzer, 2002) and to lead to increased ability to solve physics problems systematically (Wenno, 2015). Improved problem solving ability impacts the students' development of positive attitude toward physics (Erdemir, 2009; Wenno, 2015). When students gain conceptual understanding of the complex physical world, solve problems related to such complexity and develop positive attitude toward the subject, relational understanding of physics is derived from them, thereby indicating a better transfer of learning (Uhden and Pospiech, 2011). This horizontal articulation contributed to the higher achievement of students in secondary physics.

Secondary mathematics and advanced physics

G8 mathematics and advanced physics were negatively yet not significantly correlated with one another. This means that there was no significant association that existed between secondary mathematics and advanced physics. While high school mathematics is significantly correlated to high school physics, secondary mathematical concepts and skills are inadequate to contribute significantly to the achievement in advanced physics. Poor or inadequate mathematical concepts and skills become a problem in physics teaching and learning (Reddy and Panacharoensawad, 2017).

Advanced physics and advanced mathematics

Advanced courses in physics and mathematics had a positive relationship but not significantly correlated. This gives the idea that advanced courses have not contributed much to each other's achievements. This may be due to the fact that higher academic courses are considered to be separate subjects that students can study without the need of the other subjects, thereby inculcating to the minds of the students that mathematics and physics are unrelated (Clay et al., 2008; Kapucu et al., 2016). As these subjects are considered unrelated, unfamiliarity on the use of physics context in mathematics will eventually lead to a difficulty in the transfer of learning in physics (Nilden et al., 2013).

CONCLUSION

Interplay between mathematical skills and physical concepts in context plays an essential role in the achievement of students in physics. This interplay is shown in the positive significant association between mathematics and physics in elementary and high school level, signifying the essence of prior physics knowledge and foundational mathematical skills in the physics-mathematics interface for better learning. However, physics and mathematics in mixed-levels and advanced levels do not have significant relationships, recommending alignment of learning competencies between high school, senior high school, and even college.

Implication to Physics Education in the Philippines

Based on the findings of the study, the following implications are derived for the teaching and learning of physics to the Filipino students:

Facilitative and Progressive Skills Development

Basic concepts, processes, and understanding on physical phenomena should be introduced in elementary years, at least in the 4^{th} grade, to facilitate progressive development of physics skills in the elementary level. This facilitative and progressive skills development is essential in the training of Filipino students to become critical problem solvers and informed decision makers in the society.

Horizontal Articulation

Basic mathematical concepts and skills should be aligned with the skills needed in elementary physics and other science subjects. Likewise, intermediate mathematical concepts, analytical, and problem solving skills should be in coherence with the physics taught in the secondary level. Moreover, the advanced courses in mathematics and physics in the tertiary level should supplement one another, and thus, these subjects should be put together in one semester, or the mathematics subjects prior to the enrolment of the physics subject. This facilitates better utility of mathematics in physics as the language of the science course.

Vertical Articulation

Implementation of a vertically articulated curriculum ensures the students of developmental progression in applying intermediate concepts to both basic and complex situations in senior high school and tertiary levels. Equally important to such articulation is the adequacy of the pre-requisite knowledge and skills in high school physics needed for the attainment of better learning in further physics courses. For example, mechanics and fluid mechanics should be taught first to the students, then to electricity and magnetism, electronics and thermodynamics, and ultimately to more complex courses such as waves and optics and modern physics. In this way, articulation, sequence, and continuity of physical concepts are observed by the students, hence, leading to better graduates of physics and other allied sciences.

Teaching of Math to Science Teachers

Since mathematics is considered to be the language of science, teachers handling science subjects, including physics, should be taught the concepts and skills of mathematics, corresponding to the level where teachers give instruction. For instance, teachers handling Grade 7 students and teaching basic mechanics should know how to apply basic tenets of primary and intermediate Algebra. Likewise, mathematics teachers should know how to contextualize their mathematical problems and illustrations to the physical world such as the application of algebraic equations to linear, parabolic, and circular motions.

Conceptual, Qualitative, and Mathematical Teaching Models

Physics education should include not only the conceptual aspects of physics but also the qualitative and mathematical

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teaching models. Conceptual understanding of the physical world, coupled with the qualitative perspective of the different systems such as free-body diagrams, thermodynamic systems, and frames of references are needed to provide the visualization of how physics concepts work in the real world. The mathematical models create the symbols of which physics may be understood well. The combination of these models creates a complete picture of understanding physical phenomena, impacting a development of positive attitudes toward the subject. Eventually, this leads to more students taking up physics in college and to more graduates who could improve the daily living of Filipino amidst the era of rapid technological development outside the country.

Limitations and Future Directions

This correlational study was limited only to using TIMSS data from six countries that participated in Grade 4, Grade 8, and advanced level achievement tests in the years 2007, 2011, and 2015, and the implications coming from the correlational results were specially formulated for the Philippine setting, although the implications may apply to other countries with the same physics teaching-learning situations as that of the Philippines. Future researchers may use the results as baseline data for further investigations about physics teaching. Results of the 2019, TIMSS tests may be explored to expose relationships, implications, and possible policy recommendations for countries involved as well as those countries that benchmark others.

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