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Abstract

New approaches to instruction are needed in all educational levels in order to develop the skills suited to the twenty-first century (i.e., inquiry, problem solving, innovation, entrepreneurship, technological communication, experimental design, and investigativeness). This research evaluated the outcomes of an approach aiming to develop such skills based on students' assessments of themselves and their peers with regard to investigative projects and course grades. The study is chiefly based on a quantitative paradigm with a multi-method approach. Data were primarily collected using a form to evaluate scientific investigation skills and learning gains; students' project reports and examination papers were the other data sources, which were evaluated both quantitatively and qualitatively. The results revealed a low-to-moderate level of improvement in skills. In addition, the authors discovered that students were overestimating their gains, and that peer-evaluations seemed to function better than self-evaluations.

Introduction

Higher order learning outcomes in physics courses coincide significantly with several important engineering program outcomes (Çorlu & Corlu, 2012). According to the Accreditation Board for Engineering and Technology (ABET [2014]), these learning outcomes include the ability to (a) apply mathematical, scientific, and engineering knowledge; (b) design and conduct experiments, as well as analyze and interpret data; (c) communicate effectively; and (d) recognize the need for and ability to engage in lifelong learning. The development of the aforementioned skills is required in many different industries, and such development can be accomplished through teacher training programs, particularly in STEM areas (Bybee, 2010; Çorlu & Corlu, 2012; Erdogan, Corlu, & Capraro, 2013). Indeed, inquiry, problem solving, innovation, entrepreneurship, technological communication, experimental design, and investigativeness are considered necessary twenty-first century skills by academics (e.g., Binkley, Erstad, Herman, Raizen, Ripley, & Rumble, 2010; Rotherham & Willingham, 2010) in addition to various governmental and non-governmental organizations.

Nations that utilize innovative production technologies within a productive economic structure are afforded opportunities for sustainable economic growth, and are capable of creating new areas of employment (Bybee, 2010; Next Generation Science Standards, 2013; Turanlı & Sarıdoğan, 2010). According to the World Economic Forum's (2015) 144-nation Global Competitiveness Index, Turkey ranked between 55 and 131 in terms of the index's educational components (see Table 1). Countries that ranked higher (such as the United States and many members of the European Union) exerted greater effort in enacting educational strategies, plans of immediate action, and reforms intended to boost educational quality, particularly in STEM areas (Bybee, 2010). Turkey, on the other hand, has lagged behind its own standards for teacher education development, which were established two decades earlier by the National Education Development Project.

The United States is attempting to increase its educational quality (and by extension competitiveness) by implementing the integrated STEM approach, in addition to its own Next Generation Science Standards (Bybee, 2010; Çorlu, 2014; Cifuentes & Özel, 2009; Özel, 2009). These standards were developed by a consortium of 26 states in conjunction with the National Science Teachers Association, the American Association for the Advancement of Science, and the National Research Council in an effort to promote prerequisite contemporary skills. It is necessary for Turkey to take similar steps in order to increase its competitiveness, and thus thrive in today's free market economy wherein innovation and entrepreneurship are key factors (Turanlı & Sarıdoğan, 2010). To accomplish this, however, novel approaches to instruction are needed at all levels of education.

Table 1. Rankings of Turkey's educational components according to the World Economic Forum's 2014–2015 Global Competitiveness Index

	Educational component	Rank/144
1	Technological readiness	55
2	Quality of higher education	85
3	Labor market efficiency	131
4	Quality of management in schools	100
5	Quality of on-the-job training	67
6	Extent of staff training	91
7	Internet access in schools	58
8	Quality of science and mathematics education	98
9	Innovation	56

Knowledge, skills, and beliefs (which are constructed collaboratively at the intersection between multiple STEM subject areas) constitute the foundation of STEM education (Corlu, Capraro, & Capraro, 2014). Curriculum integration, which provides a theoretical framework for STEM education, is an extension of Dewey's progressive education approach, wherein the meaningfulness of subject matter to students is increased by establishing connections within and beyond school curricula (Beane, 1997). The commonality between real-life problems and those faced in business contexts is that their solutions require multidisciplinary approaches. Hence, to solve problems in the future, individuals will need to approach given issues by using integrated knowledge. In that respect, the integrated STEM approach can be utilized to develop such skills.

The present research evaluated the outcomes of an approach designed to nurture skills that are required in the twenty-first century. This approach encompassed the implementation of a course intended to improve scientific investigation skills among first-year engineering and mathematics students at a private university in Turkey. To evaluate this approach, the authors examined students' self-evaluations and the assessments of course instructors regarding learners' levels of scientific inquiry. The authors also investigated whether instructors' evaluations of student performance were significantly regressed by the evaluations of students and their peers with respect to learning gains. More specifically, the authors examined how well students integrated physics and mathematics knowledge in investigating (with the use of computer technology) pre-assigned research questions, and the extent to which they managed to assess their peers' investigative projects in addition to their own.

Method

This study is primarily based on a quantitative paradigm with a multi-method approach. Regarding the types of inquiry employed, explanatory and descriptive forms were generally used (Robson, 1993). The study can be considered explanatory because it addresses the influence of a particular teaching design; likewise, it is descriptive since it examines student misconceptions. Although the collected data were analyzed both qualitatively and quantitatively, quantitative techniques (e.g., descriptive/correlational statistics and effect sizes) were predominately used.

Participants

The participants (N = 125; 67 female) included first-year mathematics (n=56), computer (n=29) and industrial (n=40) engineering students attending a mid-level (in terms of admission scores) private university in Istanbul. Most of the students were graduates from either state (47%) or private (53%) high schools. The sample was drawn using a convenient sampling method.

Data Collection and Analysis

Data were mainly collected using evaluation forms for scientific investigation skills and learning gains; students' project reports and examination papers were the other sources, which were assessed both quantitatively and qualitatively in order to obtain further information concerning their skill development. Students assessed their learning gains in investigative projects using the Writing a Scientific Research Paper (WSRP) form developed by Cothron, Gıese, & Rezba (2005). Items from Lawson (1995) and Flick and

Tomlinson's (2006) surveys were also integrated to create the Learning Gains Evaluation Form (LGEF), which was used to assess students' perceived learning gains. Nineteen Likert items on a three-point scale (see Table 2) comprised the LGEF, which was administered to students though a web-based survey. The LGEF was used in conjunction with the retrospective post-then-pre test method (Howard, 1980), as it is advantageous in self-assessing perceived changes among many attitudinal and non-attitudinal variables (Süzük, Çorlu, & Gürel, 2011). The LGEF survey contained three dimensions: hands-off skills (LGEF1), hands-on skills (LGEF2), and general skills (LGEF3 [see Table 2]).

Table 2. Learning gains evaluation form

LGEF1. HANDS-OFF SKILLS
Naming the project and experiment
Hypothesis generation
Defining the independent variable
Defining the dependent variable
Locating variables on the axes
LGEF2. HANDS-ON SKILLS
Placing data onto the measurement table
Placing data onto the graph
Recognizing the research method
Recognizing errors through repeated measurements
Identifying a curve that matches the data / Identifying a fitting curve
R-squared interpretation of the curve equation
Comparing curve equations to the brands
Comparing bar charts to the brands
LGEF3. GENERAL SKILLS
Obtainment of research skills
Development of self-assessment skills
Utilization of peer evaluation
Providing suggestions for improvement
Identifying new research examples

This research relied primarily on students' self-evaluation data from the LGEF, whereas their project works were assessed using the WSRP. Three agents assessed the latter forms (i.e., students, peers in their groups, and the course instructor) using a numerical categorization, wherein points were awarded according to the accuracy of a respondent's answers. Fully and partially correct responses were awarded 3 and 2 points respectively, 1 point was allotted to incorrect answers, and a 0 was given in cases in which no response was provided. The course instructor also assessed students' projects from a qualitative perspective in order to identify possible misinterpretations. The following tools were used to collect data regarding course activities: (a) students' project reports concerning the three sets of experiments, (b) WSRP self- and peer-evaluations from members of the working teams, and (c) LGEF research project assessments from students, their peers, and the course instructor.

Course Implementation

The physics course's implementation was built upon a STEM-integrated, project-based learning approach. This decision was founded upon the assumption that an extensive constructivist learning environment capable of meeting the ABET (2014) outcome criteria could be realized through student-conducted research projects. It was further assumed that completing these projects would nurture students' abilities to solve problems, communicate effectively, work collaboratively, and innovate—which are all prerequisite skills for a successful engineer. Moreover, students were expected to enhance their thinking skills, better understand relationships between mathematical functions and real world concepts, and to develop an awareness of the importance of laws of physics and mathematics in explaining cause and effect relationships.

While teaching, the instructor made use of tasks designed to facilitate an inquiry-based environment in an effort to integrate students' knowledge of physics with mathematics and engineering through the use of computer software in assignments both inside and outside the classroom. The instructor also used demonstration experiments as an auxiliary technique, and assigned homework in order to observe students' progress in making inquiries. A midterm examination, quizzes, homework, and investigative projects were used both for grading and informative purposes; the Internet was used as a basic source for knowledge and data gathering. Data was collected online to obtain information concerning student progress for the purpose of assessing quizzes, homework, and the aforementioned investigative projects. Ill-defined tasks and well-defined outcomes (Capraro, Capraro, & Morgan, 2013) coupled with well-designed projects are fundamental to the inquiry approach adopted by this study. Well-defined outcomes for the course were established according to the ABET criteria (i.e., 3a, 3b, 3g, 3i [2014]); each criterion was subsequently assessed according to different LGEF survey items. For example, 3a and 3b were assessed by LGEF1 (hands-off skills) and LGEF2 (hands-on skills) respectively, whereas 3g and 3i were assessed using LGEF3 (see Table 2). Hence, the student projects facilitated a learning environment wherein twenty-first century skills could flourish.

The investigative projects were assigned randomly to groups of two to three students, and consisted of three different sets of laboratory experiments of varying difficulty that could be conducted in six different ways. In addition, students could seek guidance concerning their projects outside of class hours on a voluntary basis throughout the semester. Each group was required to plan, prepare, and present the findings of their respective experiments; it was assumed that students lacked any prior knowledge of the experiments' underlying theoretical formulas. The first set of questions involved a water tank, and asked students to consider (a) how the duration of water release changes based on the number of holes in a tank, and (b) how the depth of water in a tank changes in relation to time as water escapes from one hole. The second pair of questions concerned a paper bridge, and prompted learners to reflect on (1) how a paper's length might affect a bridge's load capacity, and (2) how a paper's thickness might affect its load capacity. The final two questions involved paper towels, and asked learners to determine (i) the water absorption capacity of various towel brands, and (ii) how the height of water (in centimeters) absorbed by the towels changed over time.

As they conducted their work, the groups recorded their observations as explanatory narratives. They also videotaped their experiments, and completed surveys that were administered both during and afterward. In addition to designing the experiments, students developed laboratory instruments and compiled a report summarizing their work. Each group member likewise evaluated their own performance as well as their peers', including their respective learning gains. At the course's conclusion, student performance was evaluated by means of a final examination, which included investigative questions regarding, for example, factors that affect the dissolution of medicine in water, and a runner's performance on a treadmill. The LGEF and WSRP surveys were administered online and used as post-course evaluation instruments.

Findings

Quantitative Findings

The results (see Table 3) revealed a strong practical significance between the pre- and post-course differences. Indeed, the effect size calculations showed large to very large effects for each scale and subscale. For example, effect size values for subscales were very close for LGEF1 ($d = 0.92$; $p < .001$), LGEF2 ($d = 1.03$; $p < .001$), and LGEF3 ($d = 1.03$; $p < .001$). The reliability coefficient values varied between medium to high (0.58–0.90), and the posttest reliability values for all measures were significantly and consistently higher than for the pretest.

Table 3. Learning gains in students' investigative projects according to their self-evaluations

	LGEF	LGEF1	LGEF2	LGEF3
Pre-test ± *SD*	7.22 ± 0.68	10.17 ± 2.30	17.67 ± 3.98	10.05 ± 2.12
Post-test ± *SD*	8.68 ± 0.58	12.49 ± 2.69	21.99 ± 4.36	12.49 ± 2.56
Gain (effect sizes)	*Cohen's d* = 2.31 ($p < .001$)	*Cohen's d* = 0.92 ($p < .001$)	*Cohen's d* = 1.03 ($p < .001$)	*Cohen's d* = 1.03 ($p < .001$)
Statistical power	100%	100%	100%	100%
Pre-test reliability (Cronbach's α)	0.86	0.67	0.80	0.58
Post-test reliability (Cronbach's α)	0.90	0.84	0.87	0.80
Pearson's *r*	.36 ($p < .001$)	.30 ($p < .001$)	.45 ($p < .01$)	.48 ($p < .001$)

The scientific inquiry scores of students as measured by the LGEF were examined in terms of their correlations with the self- and peer-evaluations of their respective projects to the WSRP and course grades (see Table 4). In general, the correlation coefficients were significantly different from zero between measurements of the LGEF and WSRP surveys. Furthermore, course grades correlated significantly with WSRP peer-evaluations (r = .212, p < .01) and LGEF (r = .236, p < .01), LGEF1 (r = .359, p < .01), and LGEF2 (r = .191, p < .01) post-evaluations, in addition to LGEF1 pre-evaluations (r = .229, p < .01). WSRP self-evaluations of the projects correlated most strongly with LGEF2 (r = .451, p < .01; r = .371, p < .01); WSRP peer-evaluations of projects were generally high at the p < .01 level between all LGEF measurements. Likewise, correlations between peer-evaluations were generally higher than those between self-evaluations.

Table 4. Correlation matrix for self- and peer-evaluations (Pearson's *r*)

Mean *SD*	WSRP (self)	WSRP (peer)	LGEF (pre)	LGEF (post)	LGEF1 (pre)	LGEF1 (post)	LGEF2 (pre)	LGEF2 (post)	LGEF3 (pre)	LGEF3 (post)	Course grade
WSRP (self) 46.94, 9.47	1										
WSRP (peer) 56.30, 14.38	.617 (**)	1									
LGEF (pre) 37.89, 7.21	.378 (**)	.491 (**)	1								
LGEF (post) 46.96, 8.68	.280 (**)	.565 (**)	.360 (**)	1							
LGEF1 (pre) 10.17, 2.30	.169	.255 (*)	.828 (**)	.222 (*)	1						
LGEF1 (post) 12.49, 2.69	.201 (*)	.464 (**)	.290 (**)	.903 (**)	.299 (**)	1					
LGEF2 (pre) 17.67, 3.98	.451 (**)	.518 (**)	.911 (**)	.348 (**)	.631 (**)	.238 (*)	1				
LGEF2 (post) 21.99, 4.36	.371 (**)	.531 (**)	.374 (**)	.938 (**)	.190 (*)	.783 (**)	.446 (**)	1			
LGEF3 (pre) 10.05, 2.12	.249 (*)	.426 (**)	.759 (**)	.316 (**)	.523 (**)	.207 (*)	.516 (**)	.220 (*)	1		
LGEF3 (post) 12.49, 2.56	.052	.446 (**)	.267 (**)	.817 (**)	0.107	.656 (**)	0.158	.626 (**)	.474 (**)	1	
Course grade 3.35, 1.70	.043	.212 (*)	.077	.236 (*)	.229 (*)	.359 (**)	.027	.191 (*)	-.040	.049	1

Notes: ** p < .01; * p < .05

Qualitative Findings

Students' project reports and responses to specific exam questions comprised the qualitatively analyzed data sources. With regard to students' work on their investigative projects, hands-off and hands-on skills were examined thoroughly. Hands-off skills include those required prior to conducting measurements or analyses, whereas hands-on skills involve those necessary for design and to perform measurements and analyses. The hands-off skills investigated specifically in this context consisted of hypothesis formulation and the definition of independent, dependent, and control variables. To obtain a deeper understanding of learners' hand-off investigation skills, a performance question asked pupils to consider how the quantity of caffeine in Turkish coffee drinkers changes in relation to time. In doing so, students were required to identify independent, dependent, and control variables, in addition to a research hypothesis (Winston, Zunker, Dover, & Andereasen, 2010).

Responses to the aforementioned question were analyzed descriptively. Although most students provided the correct hypothesis and dependent variable (74% and 62% respectively), only 16% and 13% respectively supplied the correct independent and control variables (see Table 5). In general, variables were stated in a non-quantifiable form (e.g., caffeine) or by using non-quantifiable variables (e.g., caffeine, age, weight, gender); this, in turn, often led to erroneously stated hypotheses. In addition, hypotheses were not stated in the propositional form. For example, sentences lacked words such as "is" and "are," which were replaced by "might" and "must" (e.g., "The length of time that coffee remains in one's body might vary between individuals"). Likewise, incomplete sentences were used for some hypotheses (e.g., "Time passes for coffee to leave the body" and "Quantity"). Students also tended to confuse dependent and independent variables (e.g., "time" versus "quantity of caffeine"). Furthermore, students failed to recognize independent and control variables, as they were not stated explicitly in the problem.

Table 5. Sample responses to the performance question

Independent variable	**Dependent variable**	**Control variable**	**Research hypothesis**
16%	62%	13%	74%
Coffee	The person	Caffeine	Quantity
Hour	Amount of caffeine in the body	Amount of coffee consumed	The length of time that coffee remains in one's body might vary between individuals
Time to drink	Quantity of coffee	Coffee density	Time passes for coffee to leave the body
Caffeine	Time	The person	The length of time that coffee remains in one's body varies between individuals
Time	Quantity of caffeine	Age, weight, gender	The quantity of caffeine decreases with time
Time	Length of time that coffee remains in one's body	The person; time interval	The quantity of caffeine decreases with time
Time	Length of time that coffee remains in one's body	Quantity of caffeine consumed	The quantity of caffeine must decrease with time
Time	The amount of caffeine remaining in one's body	Caffeine	

The other element examined by means of qualitative analysis concerned students' hands-on skills as observed during the completion of their investigative projects. In general, the ability of learners to graph data and perform measurements was not problematic (Aydin & Delice, 2007), although some errors were made in placing variables onto their respective axes. Similarly, students encountered difficulties in locating the line or curve of best fit (see Figures 3–4 and 6). Additionally, groups tended to draw linear equations in cases wherein curvilinear relations were more appropriate, as the former option is the easiest (see Figure 4). The most common mistakes, however, were caused by not considering or incorrectly conceptualizing limits and derivatives. Moreover, in many instances students did not seem to consider whether their findings indeed reflected reality. The cases that follow extracted from students' investigative projects demonstrate some of the aforementioned mistakes.

Case 1

In the paper towel experiment, water absorption reaches infinity with the passing of time. As absorption reaches infinity, the Brand X towel is unable to absorb all of the tank's available water. Hence, the regression equation cannot be linear (see Figures 1–2).

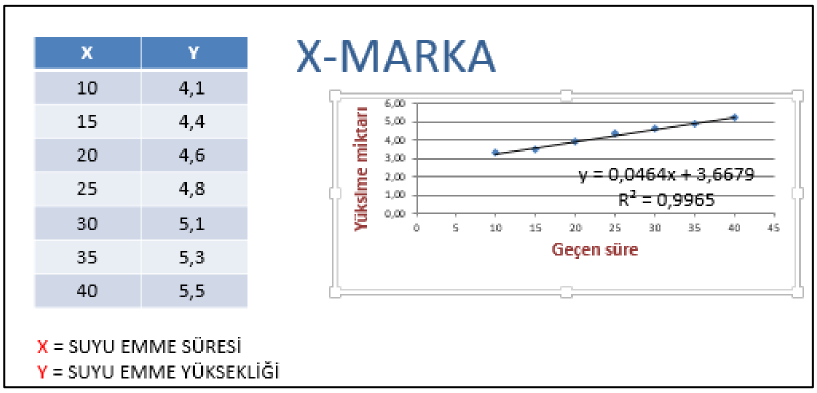

Figure 1. Limit misconceptualization for the paper bridge experiment (first example).

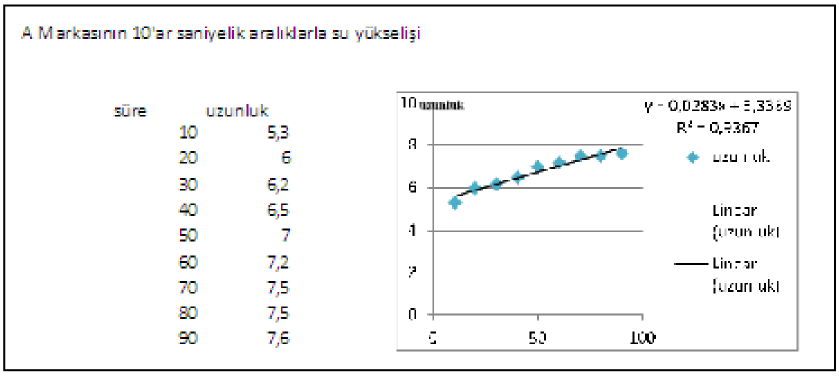

Figure 2. Limit misconceptualization for the paper bridge experiment (second example).

Case 2

As time approaches infinity, the paper towel's absorption power verges on zero—a generalization that is applicable to all brands. In Figure 3, the most powerful towel is correctly identified, as the absorbed quantity increases over time regardless of brand. The problem in this graph concerns the derivative (which defines absorption power), given that it generally reaches zero over time. However, that is not the case with this equation: the limit at $x = 0$ for the derivative of $y = 1{,}5743x^{0{,}3151}$ is not zero. Hence, the absorption power does not reach zero in this group's work, thereby implying that the towels' absorption powers are infinite.

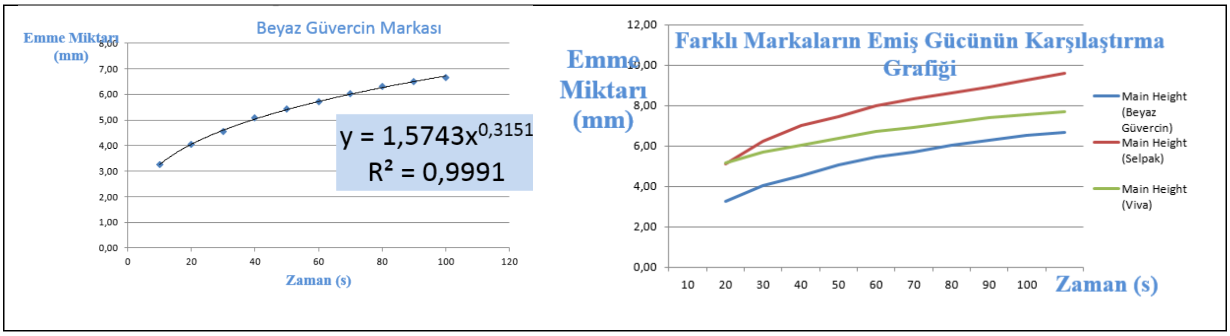

Figure 3. Limit misconceptualization for the paper towel experiment.

Case 3

In some groups, the inverse or direct proportionality of variables were not afforded sufficient attention; such instances involved scenarios wherein students did not consider their findings in relation to how certain variables occur in real life contexts. For example, in one group's project report students observed that, as the distance between two of the paper bridge's abutments decreased, so did the paper's length; consequently, the group deduced that the bridge's load capacity would also decrease. However, this claim contradicts the regression limit in the equation drawn by the group (see Figure 4). Thus, the inverse proportionality of the variables was not understood.

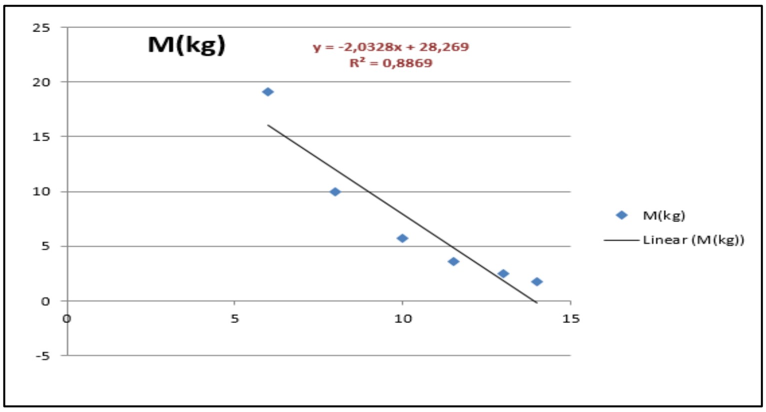

Figure 4. Proportionality misconceptualization for the paper towel experiment.

Discussion and Conclusion

In terms of the WSRP, significant correlations were identified between the peer- and self-evaluations ($r = 0.617$, $p < .01$), as shown in Table 4. In addition, the results revealed relatively substantial correlations between students' evaluations of the WSRP and LGEF; correlations were also significant between the WSRP peer- and self-evaluations when compared to the LGEF and its subscales. As shown in Table 4, WSRP peer-evaluations correlated much more strongly with the course grades when compared to the self-evaluations ($r = 0.212$, $p < .01$). These findings suggest that the peer-evaluations were superior to the self-evaluations.

Despite the large effect sizes obtained from students' evaluations of their course gains by means of the LGEF, the actual magnitude of these gains could be less (see Table 3). Given the low-to-medium correlation coefficients between the course grades and scientific inquiry test scores, in addition to the LGEF and its subscales, it is more realistic to conclude that the course's effect on students' skills was low-to-moderate. Indeed, the qualitative findings support this cautious optimism.

Leinhardt, Zaslawsky, and Stein (1990) maintain a distinction between quantitative and qualitative graphics; whereas the former can be illustrated using tables or functions, the latter involves an event. A similar distinction can be made with regard to students' interpretations of the graphs (i.e., a quantitative versus qualitative understanding). The approaches observed during the investigative projects suggest an inadequate qualitative understanding of the cause and effect relationship between independent and dependent variables (Özgün-Koca, 2013; Tairab & Khalaf Al-Naqbi, 2004). Although students were relatively successful in carrying out the experimental design's mechanical requirements (e.g., placing data onto measurement tables and graphs), they were unable to identify the best-fitting equations or interpret the R-squared error values (Aydin & Delice, 2005). Moreover, the data revealed inconsistencies between the curve equations created by students and their real life outcomes; these inconsistencies can likely be attributed to an inability to correctly interpret graphics, which itself is rooted in an incomplete understanding of physics and/or statistics and mathematics (McDermott, Rosenquist, & van Zee, 1987; Capraro, Kulm, & Capraro, 2005; Planinić, Milin-Šipuš, Katić, Ivanjek, & Sušac, 2012). An inadequate understating of limits and derivatives were likewise made evident by students' misinterpretations of the graphical data (Bingölbali, 2013; Özmantar & Yeşildere, 2013).

Responses to the performance question revealed that students were generally unsuccessful in identifying control and independent variables when attempting to solve hands-off research problems. This, by extension, affected learners' hands-on skills, and hindered their ability to identify a fitting curve and compare curve equations or bar charts to different brands. In addition, analysis of students' self-evaluations revealed a tendency to overestimate gains. High gains in the self-evaluations (as demonstrated by their high effect sizes) were not generally reflected in students' projects—at least in terms of their ability to qualitatively interpret graphs. This may be attributable to the long-term effects of students' pre-university schooling, which was not based on integrated STEM approaches (Ayas, Aydin, & Corlu, 2013). Likewise, learner incompetence with regard to hands-on and hands-off skills could be due to below average academic levels, as many students' entrance scores did not satisfactorily meet the engineering program's requirements (Ölçme, Seçme ve Yerleştirme Merkezi [OSYM], 2015).

In the United States and European Union, STEM education has received significant governmental and institutional support; nevertheless, an equally comprehensive awareness has not yet materialized in Turkey, despite the presence of groups such as *Fen, Teknoloji, Mühendislik ve Matematikthe* (the Task Force on STEM Education). Furthermore, the closure of many science faculty programs has negatively impacted student placement rates in STEM areas (Istanbul Aydin University, 2014; OSYM, 2015). Hence, the enhancement of student performance in fields such as science, technology, engineering, and mathematics is largely dependent on increased institutionalized support for integrated STEM approaches in Turkey.

Notes

This study's findings were presented at the fourteenth *Ulusal Fen Bilimleri ve Matematik Eğitimi Kongresi* (National Science and Mathematics Education Congress) held on September 11–14, 2014 at Çukurova University, Adana, Turkey.

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