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Teaching Newton's Laws to Urban Middle School Students: Strategies for Conceptual Understanding

Angela M. Kelly
Lehman College

Ross Kennedy-Shaffer
Hunter College High School

Abstract

Participation in secondary physics has been shown to be limited for underrepresented students in urban school districts. This study explores an alternative means for providing physics access for city youth through the use of a university-based Saturday enrichment program for eighth grade Latino students. During a three-week unit on Newton's laws, students engaged in inquiry-based lessons that featured hands-on tasks, probeware with handheld sensing devices, computer simulations, iPod Touch applications, and multiple representations of mechanics concepts. Students were tested pre- and post- with a modified Force Concept Inventory. Results indicated significant gains in student understanding of Newton's laws. Implications for physics teaching and learning in urban middle schools and informal science settings are discussed.

In U.S. secondary schools, there is a persistent lack of access to formal physics instruction for low-income urban students. Although approximately 37% of all American students have graduated high school after taking at least one physics course (American Institute of Physics, 2009), just 15% of students have taken physics in urban areas such as the Bronx (Kelly & Sheppard, 2009). Recent research has advocated for expanded accessibility through the improvement of instructional strategies and an increased emphasis on the practical relevance of physics concepts (Basu, 2008; Haussler & Hoffmann, 2000). In response to the need for early exposure to the physical sciences, the Bronx Institute at Lehman College has offered conceptual physics courses to secondary students on weekends for the past three years. In a recently designed course, a cohort of Latino eighth graders enrolled for weekly informal classes, and the authors (a science education faculty member and a second-year high school physics teacher) co-taught a unit on forces. Using research-based instructional strategies and educational technology, we hoped to connect physics principles to students' everyday lives to promote their understanding of and interest in physics.

The rationale for this study is based upon the need to improve physics access and participation for underrepresented minority students. The persistent issue of limited access to physics education for urban students is problematic for several reasons. Few underrepresented students choose to pursue post-secondary science, technology, engineering, and mathematics (STEM) related studies and careers (National Academies of Sciences [NAS], 2007), and the proportion of those participating has indeed diminished over the last twenty years (Lewis, Menzies, Najera, & Page, 2009). The exclusion of a significant part of the U.S. population from science and technology will have a lasting impact on workforce diversity and global competitiveness (NAS, 2007). Consequently, there needs to be a greater focus on making access to physics education more equitable for urban youth. Early exposure to physics through high-quality physics instruction has been shown to improve interest in the field and promote continued participation (Gorard & See, 2009).

The physics class described in this study was designed to maximize middle school student engagement and understanding, and demonstrate the relevance of physics to their personal lives and future goals (Basu, 2008; Haussler & Hoffmann, 2000). Traditional, lecture-based teaching methods have often been unsuccessful in altering students' prior views of physical phenomena, and there has been considerable research on more progressive teaching practices. Student engagement promoted through self-expression has been particularly effective (Morote & Pritchard, 2002). Children need to make sense of conflicting observations through reflection and social interactions before their thinking becomes more aligned with scientifically accepted ideas (Driver, Asoko, Leach, Mortimer, & Scott, 1994; Gunstone & Watts, 1985).

Besides verbal modes of expression, changing word descriptions into physical, graphical, and pictorial representations has helped students make sense of complex ideas in physics (Van Heuvelen, 1991). Learning environments that emphasize models and representational symbols have promoted cognitive gains (Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001). The *free body diagram*, a drawing of an object with the magnitude and direction of the force(s) acting on it represented by arrows, is an excellent tool for introducing basic mechanics principles (Yeo & Zadnick, 2000). When students have been trained to use free body diagrams consistently, they are more likely to answer problems correctly (Rosengrant, Van Heuvelen, & Etkina, 2009). The ability to consistently draw correct free body diagrams of physical objects has helped students disregard irrelevant contextual factors (such as what forces the object itself exerts), a common stumbling block for younger physics students (Palmer, 1997).

Digitally mediated environments are the norm for today's youth, and educational environments must incorporate these practices to maximize learning (Hsi, 2007). Kuech and Lunetta (2002) reported that real-time data sensors and graphs have engaged students in cognitive conflict and promoted conceptual growth; such tools allow students to rapidly evaluate hypotheses with multiple trials. When students have experienced the physical correlation between modeling and actual phenomena, they are more likely to confront misconceptions and develop sound understandings (Metcalf & Tinker, 2004). The digital fluency that most children bring to school must be leveraged to facilitate data collection and the evaluation of evidence (Hsi, 2007). The use of technology can also promote interest and help students see the relevance of physics concepts in their lives.

The research questions guiding this study include the following: 1) How might eighth grade students develop a sound conceptual understanding of Newton's laws, using research-based practices and the latest educational technology?; and 2) Does student performance correlate to certain student characteristics (such as GPA, gender, prior math achievement, and program attendance)?

Method

Participants

The participants in this study were enrolled in the *Enlace Program* (Engaging Latin Communities for Education) of the Bronx Institute, which hosted a Saturday Physics Program for a cohort of twenty 8th grade students (12 female, 8 male). The students were recruited from surrounding middle schools. The participants' mean grade point averages was 89.9 with a standard deviation of 3.9; the high was 99.3 and the low was 81.3. The students had all scored a 3 or 4 on the New York State standardized math exam in middle school (on a scale of 1-4).

The students in Enlace all resided in the Bronx, a high-poverty, densely populated county and one of the five boroughs of New York City. According to the U.S. Census Bureau (2000), in the Bronx, 1.3 million residents are 48.4% Latino, 14.6% White, 31.2% Black, and 2.8% Asian, and the median household income is approximately $35,000. Bronx schools typically have a > 90% population of minority students, the lowest graduation rate in the city (47.8%), and 91% of all students qualify for free or reduced lunch (New York City Department of Education, 2009). Students enrolled in the Enlace Physics Program at the Bronx Institute had never taken a formal physics course and many would not have the option during their high school years (Kelly & Sheppard, 2009).

Instruments

Students were administered two instruments to gauge their understanding of force concepts. During week 1, we administered a pre-test of eleven conceptual questions, drawing from the Force Concept Inventory, a validated high school through college-level non-quantitative assessment (Savinainen & Scott, 2002), the New York State Regents Physics Exam, and other sources. This conceptual assessment was designed to test several key concepts without mathematical knowledge, although we modified some of the wording to make the test more appropriate for middle school learners. The topics included Newton's first, second, and third laws, free body diagrams, free fall, and centripetal force (internal consistency Cronbach's $\alpha = 0.86$). At the start of class during week 4, students took the eleven-item post-test, which was similar in focus yet with differently worded questions.

Instructional Treatment

The present study highlights three specific two-hour sessions that focused on Newton's laws. As part of the semester-long physics course, the authors designed a three-week unit on forces that would allow students to relate physics concepts to their daily experiences. To achieve this, the unit focused on a graphical understanding of forces, technology applications, a conceptual analysis of Newton's laws, and various experiential learning activities (referred to as "stations") relating to mechanics and centripetal force. All of the activities were designed to address common misconceptions in the understanding of mechanics using research-based practices.

Week one. During week one (*Graphical Representations of Force*), force was defined, eliciting students' ideas through questioning and discussion, stressing the differences between their understanding of the word and its precise physics definition. Then we demonstrated how to draw a *free body diagram* depicting the magnitude, or amount, and direction of various forces acting on a singular object, modeling the technique and logical thinking for creating such a diagram. The students were given an activity in which they had to construct the free body diagrams of everyday situations (e.g., an elevator accelerating upward in the Empire State Building, a load of bricks hanging from a crane). The students were expected to practice these free body diagrams in groups of 3-4, which allowed them to apply their understanding collaboratively and create their own scenarios. We demonstrated several aspects of gravitational free fall with some mechanical models and computer simulations, showing that neither an object's mass nor its horizontal speed affects the time it takes to fall.

Week two. During week two (*Basic Conceptual Tasks*), students worked on a series of short tasks in groups (see Table 1), moving from station to station until they met the targeted outcomes. They were given materials to test Newton's first and second laws in structured and unstructured activities, relating these concepts to their daily lives in discussions about sensations they have felt in cars, subways, and buses. Students found the use of technology very engaging in the fifth station, using the accelerometer function and iPod Touch applications to explore inertia (the Awesome Ball app), centripetal, or circular, force (the Roller Coaster app), and free body diagrams (the Paper Toss app) (Kelly, 2011). Finally, students played tug-of-war using digital force probes attached to handheld computers to verify Newton's Third Law. The technology stations seemed particularly effective, since students were able to repeat their experiments and change variable values with ease.

Table 1
Mechanics Activities: Basic Conceptual Tasks (Week 2) and Newton's Laws in New Contexts (Week 3)

	Concepts	Sample Tasks	Expected Student Outcomes
WEEK 2: Basic Conceptual Tasks	Newton's 1st law	▪ Observing coins on index cards; removing the cards to see what happens to the coin.	Explain Newton's first law through physical familiarity with inertia.
	Newton's 1st law	▪ Watching film clips to observe the motion of characters without seat belts.	Understand inertia as reason for seat belts.
	Newton's 2nd law	▪ Changing the mass of a cart while the applied force remains constant, and observing the effect on acceleration.	Recognize and express inverse relationship between mass and acceleration.
	Newton's 2nd law	▪ Changing the applied force acting on a cart and observing the change in acceleration (mass remains constant).	Recognize and express direct relationship between force and acceleration.
	Newton's laws (all)	▪ Simulate the motion of objects with accelerometers (using iPod Touch). Use designated applications to manipulate variables and observe the effects on objects.	Identify forces that change an object's motion; differentiate between equilibrium and accelerating systems.
	Newton's 3rd law	▪ Using spring scales to pull against each other or passively experience forces. ▪ Operating a hovercraft and explaining the forces acting on the object to keep it elevated.	Observe and explain equal and opposite forces.
WEEK 3: Newton's Laws in New Contexts	Apparent weight	▪ Using force probes to observe changes in apparent weight in an elevator. ▪ Using a bathroom scale to observe changes in normal force in a moving elevator.	Explain the relationship between the readings and the normal force.
	Newton's 2nd law	▪ Computer simulations with PhET – manipulating forces to observe effects on objects.	Predict and analyze the effects of various forces on an object's motion
	Newton's 1st law	▪ Subway simulation – observing a pendulum as students move on a rolling chair.	Explain sensations and observations due to inertia on a moving subway train.
	Newton's 3rd law	▪ Pushing against each other with force probes and observing force measurements on the computer.	Predict, observe, and explain equal and opposite forces.
	Centripetal force	▪ Measuring the speed of a revolving mass on a string; altering the centripetal force to observe the effect on speed.	Observe that the square of speed of circular motion is directly related to the centripetal force.

Week three. During week three (*Newton's Laws in New Contexts*), students improved their comprehension of various concepts of forces through group experiments (Table 1). Students also used an online applet, Force1D, to apply their understanding of

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Newton's Second Law to the notion of equilibrium, wherein an object with no net forces acting on it will experience zero acceleration. The applet comes from Physics Education Technology (PhET), a collection of interactive applications designed by the University of Colorado (2009) to make physics more accessible. They also used the force probes to continue their work with Newton's third law.

Design and Procedure

A *proof of concept* approach was employed in this study, whereby research-based strategies were implemented with a small pilot group. Data collection was designed to provide support for expanding our methods with future cohorts of middle school physics students. Scores on the pre-post achievement assessment instruments were summarized. They were also analyzed by topic: free body diagrams, Newton's first law (inertia), Newton's second law (and equilibrium), Newton's third law, free fall, and centripetal force.

A number of factors were explored informally using multiple regression models for their possible correlations with the achievement results, including gender, GPA, prior math achievement on the NY State standardized tests, and students' attendance at the three sessions during which forces were taught.

A paired-sample t-test was used to compare the pre-test and post-test scores. Cohen's d was used as the benchmark for large (0.8), medium (0.5), and small (0.2) effect sizes (Cohen, 1988). Descriptive statistics such as means and differentials were used to examine individual students' progress and how well they understood particular sub-topics. In addition to the descriptive statistics, a second multiple regression model was used to explore relationships of pre-test scores, gender, attendance, GPA, and prior math achievement as the predictors of pre-post student growth.

Results

Physics Achievement Scores

Table 2 summarizes the pre-post achievement gains for the group overall along with disaggregation by attendance, gender, and standardized math scores. Table 2 shows the largest gains observed for students with 100% attendance (18.8 percentage points), male students (15.9 points), and math level 3 students (16.1 points). The pre-post gains for the overall group tested using the t-test was significant ($t = 3.1$, $df = 19$, $p < .01$), with an effect size of 0.73 (medium). Figure 1 shows the pre-post scores for the group overall and subgroups.

Table 2
Physics Content Diagnostic Scores, Overall and Within Groups

Variable	N	Pre-test mean	Post-test mean	Pre-Post Gain
Students (all)	20	43.2	55.9	12.7
Students with 100% attendance	13	46.2	65.0	18.8
Female	12	47.7	58.3	10.6
Male	8	36.4	52.3	15.9
Math level 3 students	11	34.4	50.5	16.1
Math level 4 students	9	53.2	63.6	10.4

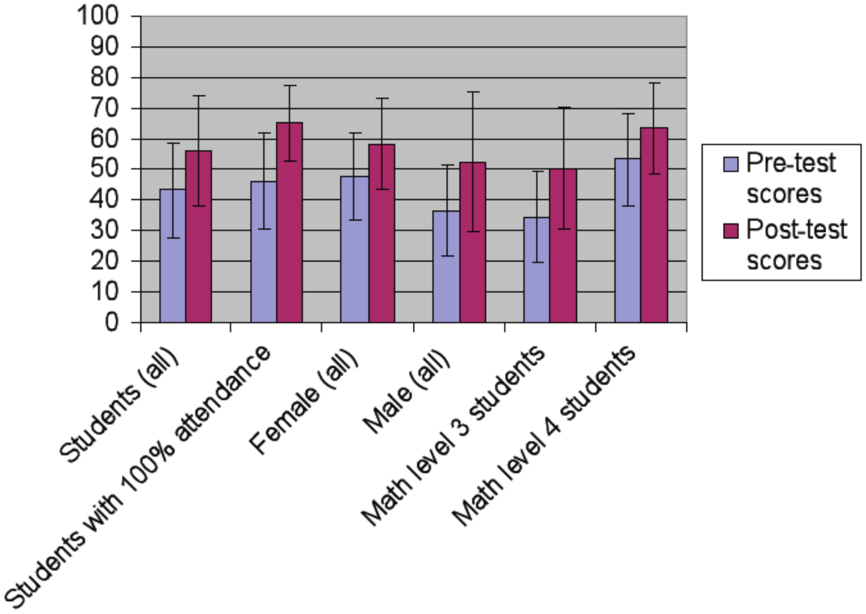

Figure 1. Pre-test and post-test scores for students, overall and within groups.

Two multiple regression models explored to what extent possible predictor variables explained student pre-post gains. The R-squared values were compared for two sets of predictor variables. The first model included two predictors: attendance and pre-test scores. The combined effect of these two variables had an R-squared value of 0.51 ($p < .01$), indicating they accounted for 51% of the variance in pre-post gains. The second model included five predictor variables: attendance, pre-test scores, gender, GPA, and prior math achievement. The R-squared value for this equation was 0.56 (*p* <

.01), accounting for 56% of the variance in pre-post gains. These models indicate that attendance and prior academic knowledge were the best predictors of performance.

Individual Performance

Individual performance was analyzed by exploring test scores as they relate to attendance. Mastery levels were determined by using benchmarks similar to the New York State Regents. To pass the NYS Physics Regents Examination in high school with a 65-scaled score, students must earn 49 out of 85 points, or 58% [New York State Education Department (NYSED), 2010]. Students above this threshold are considered to have reached mastery, while students above 70% are judged above mastery. Table 3 shows the achievement of students grouped by number of absences. All students who had achieved 70% mastery had no absences during the Newton's laws unit, as well as five of the six students who had achieved 58% mastery. Nine out of thirteen students with 100% attendance attained mastery. Students who attended all sessions increased their average score by 18.8 percentage points. Students with one absence achieved an average gain of only 6.0 percentage points, while students with two absences reported an average decrease in performance by 2.2 percentage points.

Table 3
Individual Changes in Performance on Physics Diagnostic

Number of absences during Newton's laws unit	Number of students (N)	Pre-test average	Post-test average	Number of students at 58% mastery	Number of students at 70% mastery
0	13	46.2	65.0	5	4
1	3	24.3	30.3	0	0
2	4	47.7	45.5	1	0

Understanding of Specific Mechanics Topics

The achievement tests were analyzed according to six different mechanics categories (although there was some overlap among principles). As Table 4 shows, these topics included Newton's first, second, and third laws, free body diagrams, free fall, and centripetal force. Students achieved the highest gains in questions related to Newton's first law and free body diagrams, which were taught during the first 2 sessions (see Table 4). However, scores on questions related to Newton's second law showed no gain for students with 100% attendance. Scores for Newton's third law showed a 10.0-point gain for students with 100% attendance. Large gains were noted among all students and students with 100% attendance for free fall (19.0 and 14.3 points, respectively) and centripetal force (20.0 and 23.1 points, respectively).

Table 4
Student Achievement on Specific Mechanics Topics, All Students and Students with 100% Attendance

	All Students			Students with 100% Attendance		
Topic	Pre-test mean	Post-test mean	Pre-post gain (loss)	Pre-test mean	Post-test mean	Pre-post gain
Free body diagrams	27.8	69.4	41.6	25.0	79.2	54.2
Newton’s first law	10.0	75.0	65.0	15.4	69.2	53.8
Newton’s second law	56.3	45.9	(- 9.6)	60.1	60.2	0.1
Newton’s third law	50.0	50.0	0.0	55.0	65.0	10.0
Free fall	38.1	57.1	19.0	42.8	57.1	14.3
Centripetal force	60.0	80.0	20.0	61.5	84.6	23.1

Discussion

As outlined previously, these results confirmed our belief that middle school students can learn physics with research-based instruction that incorporates appropriate technologies. Although the participants constituted a relatively small sample, the evidence of substantial growth in pre-post achievement was promising. The clinical observations from descriptive statistics revealed that students developed scientifically sound understandings of physics concepts. From the multiple regression models, it was apparent that attendance was the only significantly correlated factor with pre-post gains, suggesting that performance did not relate significantly to prior academic achievement (GPA and math achievement) or gender. This implies that lack of access to quality physics instruction, not academic or science-specific achievement may be one significant barrier to the future STEM participation of urban children (Tyson, Lee, Borman, & Hanson, 2007). Students should not have to wait until high school to learn physics, particularly when so few schools in urban areas provide the option to study it.

The average score increased for both male and female students, though males had a greater increase. We observed that both females and males actively engaged with the many activities in the classroom, though research has suggested that males are more likely to value and benefit from kinesthetic science experiences, such as building models and fixing objects (Farenga & Joyce, 1997). The structure of the physics course appeared to be an equalizer for these gender-based disparities, as the initially lower-achieving males began to close the gap.

A differential increase based on prior math achievement was also noted for both math levels 3 and 4. It is important to note that the benchmark mastery levels had been set for high school students (usually juniors or seniors), and the subjects in the present study were enrolled in eighth grade. Students with higher mathematics performance were more likely to have reached mastery, but those with lower mathematical ability made greater gains. The conceptual approach brought the lower math achievers much further towards a more complete understanding of mechanics principles. By de-emphasizing formulas and mathematical applications, the researchers were able to challenge students' thinking about mechanical processes without intimidating them (Van Heuvelen, 1991).

Mechanics Topics and Corresponding Strategies

Students made significant gains in the topics of free body diagrams and Newton's first law, and smaller gains in Newton's second law, Newton's third law, free fall, and centripetal force. We found that the technology applications were useful, but we could have improved their implementation in certain instances. The iPod Touch, PhET simulations, and digital force probes presented means to observe the immediate effects of independent variables on the motion of objects. They also allowed students to repeat experiments of their own design multiple times during class sessions. Although these tools helped students in their understanding of inertia and free body diagrams, they were less helpful with Newton's second and third laws.

The construction and interpretation of free body diagrams was reinforced in a variety of contexts; however, Newton's second and third laws were more challenging for the students. Upon reflection, we felt that the students had difficulty piecing together the steps necessary to relate acceleration to a force imbalance (second law). This complex process may have presented a significant cognitive barrier for students of such a young age. With respect to Newton's third law, that of equal action and reaction forces, we realized upon reflection that every class activity and technology application involved two equal objects, such as spring scales or force probes. Although students understood that a force cannot be exerted or experienced in isolation, they intuitively held on to the notion than the larger body exerts a greater force in an action-reaction pair. While students recognized that pulling apart on two spring scales results in equal forces on each, they may have associated that with the fact that the two spring scales are so similar. The assessment questions asked about two seemingly disparate objects, such as an insect and a windshield, whereas in class we did not adequately show that such different objects also experience equal and opposite simultaneous forces.

We also felt that students would better understand the concept of free fall if they had done their own experiments, rather than watching the instructors manipulate the computer simulation. Their personal involvement would have given them a better understanding of the motion of objects under the influence of gravity.

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Limitations

There are several limitations that could not be eliminated in this pilot study. First, the sample size is relatively low. We hope to improve our sample size by expanding our study to include future cohorts. Secondly, the students in this group are self-selecting, in that they actively applied for a program that takes place after school and on weekends. These students tend to be highly motivated and have supportive families who value educational capital, so they may be more predisposed towards academic success. Finally, there was no control group for this study; the authors selected statistical techniques to analyze the research questions through a proof of concept perspective, whereby the feasibility of the curricular design is tested with a small pilot group. Descriptive statistics informed our clinical observations and their suggested implications, though future studies with larger numbers of participants, longer interventions, and control groups would more strongly support wider implementation of our instructional strategies.

Conclusions and Implications

This pilot study of an informal physics course for 8th grade students has several important implications. The first such implication involves the promise of providing traditionally underserved students the opportunity to study physics in an engaging learning environment. Physics study should begin early in a student's academic life, which will promote their interest and potential for pursuing more rigorous physics courses later on. Instruction in the upper elementary years can introduce physics principles and provide the foundation for more in-depth physics learning. As a gateway course for STEM participation, physics access and achievement correlate with a higher likelihood of success in college science (Tyson et al., 2007). Expanding the pipeline of STEM participants, particularly in urban areas, will help diminish the ethnic and socioeconomic representation gap in the scientific community (NAS, 2007).

The pedagogical strategies employed were also essential to the program's promise. Research-based practices that incorporate hands-on tools and technology applications are important for early physics study to be successful; by using innovative technological tools, an emphasis on visual representations, discrepant events to challenge unscientific thinking, and a collaborative approach, participants were actively engaged (Driver et al., 1994; Gunstone & Watts, 1985). High-quality informal physics instruction requires intensive planning, an awareness of what knowledge and misconceptions students bring to the classroom, and coordination of experiences whereby students construct understandings through observation. By creating an environment conducive to participation and risk-taking, students experienced active learning.

Finally, this study suggests that informal settings have great potential for fostering interest in physics among students who do not enjoy access to physics and/or high quality science instruction. These students attended the program to expand their

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academic potential in ways that their neighborhood schools could not. We hope to leverage the interest of these students by offering more opportunities to study physics on the college campus, and expanding the focus of our physics courses to incorporate other topics, such as light, electricity and magnetism, mechanical energy, fluid mechanics, and motion. In this way, students can see that physics is all around them; it is an essential part of their scientific literacy and foundational science knowledge. Understanding physics can help them become more aware of the wonders of their natural world.

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About the Authors

Angela M. Kelly, **Ph.D.**, is an Assistant Professor of Science Education in the Department of Middle & High School Education at Lehman College, City University of New York. Her research explores physics and chemistry access for urban youth, educational technology in the science classroom, and pedagogical content knowledge in the physical sciences. E-mail: angela.kelly@lehman.cuny.edu.

Ross Kennedy-Shaffer teaches high school physics and eighth grade physical science at Hunter College High School in New York City. He recently earned a Master of Science degree in 7-12 Science Education from Lehman College, City University of New York, specializing in Physics Education. E-mail: rkennedy@hccs.hunter.cuny.edu.