Exploring the connection between problem solving and conceptual understanding in Physics

REVISTA DE ENSEÑANZA DE LA FÍSICA

Explorando la conexión entre la resolución de problemas y la comprensión de conceptos en Física

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(Received 5 June 2018; accepted 15 September 2018)

Abstract

This study probes whether problem solving ability is indicative of an understanding of the concepts underlying problem solutions. Low-performing students enrolled in an introductory mechanics course for scientists and engineers viewed an animated-narrated solution to a difficult problem in angular dynamics as preparation for an upcoming midterm exam. Immediately after viewing the solution, the students attempted to solve an isomorphic calculation-based problem and a conceptual question that probed whether students understood the concepts underlying the solution to the calculation-based problem. We found that ability to solve the calculation-based problem did not correlate with conceptual understanding. This suggests that, at least for low-performing students, problem solving and conceptual understanding in physics are different types of knowledge that develop independently, and as such, instruction should focus on the development of both types of knowledge rather than assuming that proficiency in solving complicated problems is indicative of conceptual understanding.

Keywords: Worked examples; Problem-solving; Conceptual understanding.

Resumen

Este estudio indaga si la habilidad de resolución de problemas es indicativa de la comprensión de los conceptos que subyacen a la solución del problema. Un grupo de estudiantes, de bajo desempeño académico, vieron una solución animada/narrada a un problema de dificultad considerable que trataba sobre dinámica angular. Esto ocurrió como parte de una preparación para un examen parcial en el contexto del curso de mecánica introductoria para científicos e ingenieros en el cual estaban inscriptos. Inmediatamente después de ver la solución narrada, los estudiantes intentaban resolver un problema que requería cálculos, pero isomorfo al del ejemplo. También respondían una pregunta conceptual que indagaba sobre cuánto habían entendido de los conceptos que subyacían a los cálculos. Se encontró que la habilidad para resolver el problema de cálculo no correlaciona con la comprensión conceptual. Esto sugiere que, el menos para estudiantes de bajo desempeño, la resolución de problemas y la comprensión conceptual en física constituyen distintos tipos de conocimiento que se desarrollan de manera independiente, y así, la instrucción debería enfocarse en el desarrollo de ambos tipos de conocimiento en lugar de dar por sentado que la habilidad para resolver problemas complicados es indicativa de la comprensión conceptual.

Palabras clave: Ejemplos resueltos; Resolución de problemas; Comprensión conceptual.

I. INTRODUCTION

Whether stated explicitly by physics instructors or assumed implicitly, two major goals in teaching introductory physics courses for scientists and engineers are to help students develop problem solving skills and to facilitate conceptual understanding. The regimen for helping students develop problem solving skills typically consists of assigning plenty of quantitative homework problems for students to solve. In terms of helping students develop conceptual understanding, considerable progress has been made over the last three decades by increasing students' in-class engagement and by probing for conceptual understanding during class time (Mazur, 1997), usually using classroom response systems (so-called clickers). Instructors can thus address conceptual misunderstandings as they occur in real-time during class sessions, thereby playing more of a coaching role for students' learning than the dispenser-of-information role common in lecture-only courses. These types of active-learning approaches are typically more effective at helping students overcome stubborn misconceptions compared to passive lecture approaches (Freeman et al., 2014; Hake, 1998).

At the University of Illinois at Urbana-Champaign we use research-based instructional strategies (Stelzer, Gladding, Mestre &Brookes, 2009; Stelzer, Brookes, Gladding & Mestre, 2010) to teach thousands of students yearly in large introductory courses. The "flipped" approach we use has students viewing animated-narrated pre-lectures (see: https://per.physics.illinois.edu/resources/interactive-online-lectures/PHYS211/Player/) prior to coming to class. In these pre-lectures, basic physics knowledge is presented so that class time is devoted to refining conceptual understanding and developing problem solving skills. In addition to incorporating aspects of the "flipped" approach, the Physics Department also transitioned from exams that consisted of working out a few calculation-basedproblems that were later hand-graded, to multiple-choice exams that assess both problem solving and conceptual understanding. Careful analysis showed that the multiple-choice exams were equally reliable and valid for evaluating student performance as the calculation-based problems where students work out solutions that are then hand-graded (Scott, Stelzer & Gladding, 2006).

Although using both types of exams is equally "good," this article will argue, and indeed demonstrate, that assessing conceptual understanding remains elusive. This article has two goals, one primary and one secondary. The secondary goal is to explore whether low-performing students enrolled in an introductory, calculus-based mechanics course can learn to solve a complicated, calculation-based problem from rotational dynamics by watching a solution video of a similar problem. The primary purpose of this article is to show that the vast majority of those students who watched the solution video and were then able to solve the problem do not display conceptual understanding underlying their solution. Related to this primary goal, we will also show that answering a multiple-choice conceptual question correctly about the same problem situation is not indicative of conceptual understanding. We conclude with an in depth look at the rationales provided by students to explain the reasoning behind their conceptual explanations.

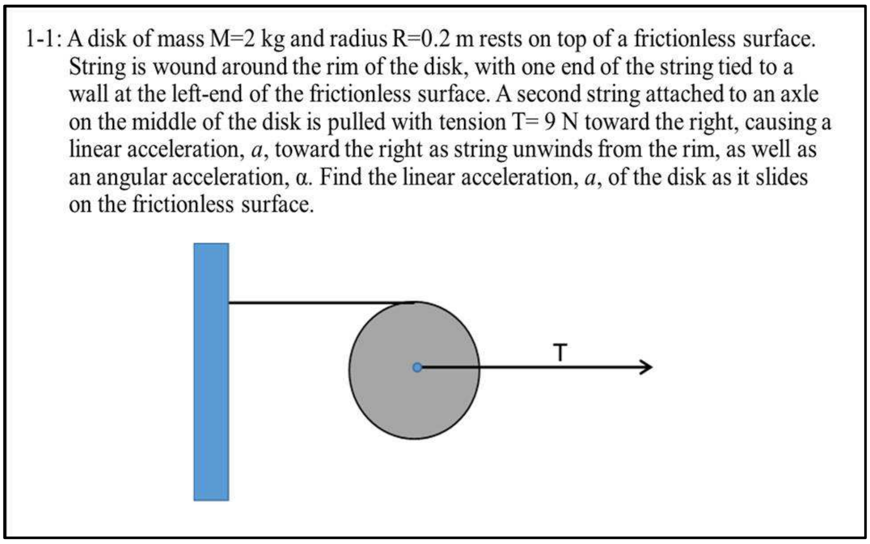
II. STUDY CONTEXT

The data presented here is part of a larger study aimed at helping under-performing students enrolled in an introductory mechanics course for scientists and engineers improve their performance on exams in the course. The study focused on material from the third exam, which covered angular motion, angular dynamics, angular momentum, moment of inertia, and equilibrium of rigid bodies. Students who had performed in the bottom third on the first two midterm exams were sent an email inviting them to participate in a study designed to help them prepare for the third exam.

Sixty-eight students enrolled in the course volunteered and were randomly assigned to one of two conditions. The two conditions investigated a research question that will not be discussed here, namely whether attempting to solve a problem prior to viewing its solution proved more beneficial for learning than simply viewing the solution without first attempting to solve the problem. Students in the first condition ($N = 30$) attempted to solve five problems similar to those that typically appear on the third exam (we will refer to this as the "pre-test"). After attempting all five problems, the students then watched animated-narrated videos of an expert's solutions to the five problems that they had attempted. Students were told that following the video solutions, they would be given a nine-problem post-test (five calculation-based, and four conceptual problems) that covered material similar to that in the pre-test and the animated-narrated solutions. The calculation-based problems that they solved following the solution videos were isomorphic to the problems in the solution videos. The conceptual problems were designed to probe the underlying concepts used to solve the numerical problems. The conceptual questions were multiple-choice questions that also asked students to provide an explanation for their answer choice.

Students in the second condition ($N = 38$) did not attempt to solve the questions on the pre-test, but instead began by viewing the animated-narrated solution videos to the five problems on the pre-test. Immediately after viewing the solutions, these students completed the same post-test as the other group. Thus, when we present the results below, we only have data on performance on the pre-test for 30 students and data on performance on the post-test for all 68 students.

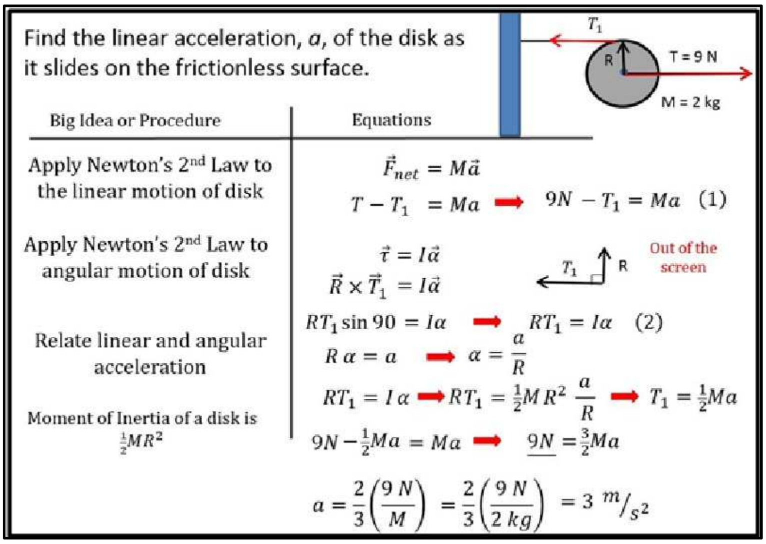
We will restrict the discussion here to one problem from the pre-test and the two related problems from the post-test, one calculation-based and one conceptual. The problem on the pre-test is shown in Figure 1 (hereafter referred to as problem 1-1). It should be noted that problem 1-1 is fairly difficult for introductory students, and involves the application of both Newton's Second law to the disk (two tension forces, and linear acceleration of the disk enter the resulting equation), and Newton's Second law in angular form, $\tau = I\alpha$, about the center of mass of the disk (one tension force and the angular acceleration of the disk about its center of mass enter the resulting equation). A third equation is needed to solve for the three unknowns (the tension of the string tied to the wall, the acceleration and the angular acceleration), namely the relationship between the angular and linear accelerations (Rα=a).



1-1: A disk of mass M=2 kg and radius R=0.2 m rests on top of a frictionless surface. String is wound around the rim of the disk, with one end of the string tied to a wall at the left-end of the frictionless surface. A second string attached to an axle on the middle of the disk is pulled with tension T= 9 N toward the right, causing a linear acceleration, a, toward the right as string unwinds from the rim, as well as an angular acceleration, α. Find the linear acceleration, a, of the disk as it slides on the frictionless surface.

FIGURE 1. Calculation-based Pre-test Problem.

The sequencing of the animated-narrated solution presented in the video for problem 1-1 is shown in Figure 2. The solution approach followed a "two-column solution" where the left column discussed the concepts being applied, and the right column showed how the concept was expressed as an equation. For those interested in watching the entire animated-narrated solution, it can be found at the following URL: https://youtu.be/V6YYWug3Lt8. The solution always presented the concept or procedure that was being applied (in the left column) and then carried it out by showing its execution (in the right column). This approach was intended to integrate conceptual and procedural knowledge with their mathematical implementation.



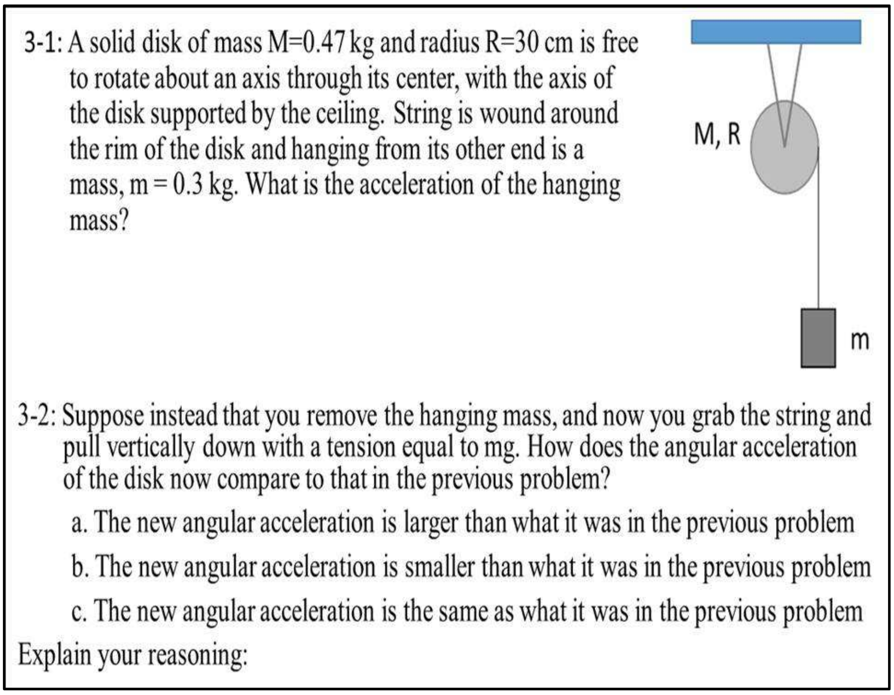
Find the linear acceleration, a, of the disk as it slides on the frictionless surface.

Big Idea or Procedure	Equations
Apply Newton's 2nd Law to the linear motion of disk	$\vec{F}_{net} = M\vec{a}$ $T - T_1 = Ma \Rightarrow 9N - T_1 = Ma \quad (1)$
Apply Newton's 2nd Law to angular motion of disk	$\vec{\tau} = I\vec{\alpha}$ $\vec{R} \times \vec{T}_1 = I\vec{\alpha}$ $RT_1 \sin 90 = I\alpha \Rightarrow RT_1 = I\alpha \quad (2)$
Relate linear and angular acceleration	$R\,\alpha = a \Rightarrow \alpha = \frac{a}{R}$
Moment of Inertia of a disk is $\frac{1}{2}MR^2$	$RT_1 = I\,\alpha \Rightarrow RT_1 = \frac{1}{2}M\,R^2\,\frac{a}{R} \Rightarrow T_1 = \frac{1}{2}Ma$ $9N - \frac{1}{2}Ma = Ma \Rightarrow \underline{9N} = \frac{3}{2}Ma$
	$a = \frac{2}{3}\left(\frac{9\,N}{M}\right) = \frac{2}{3}\left(\frac{9\,N}{2\,kg}\right) = 3\ {}^{m}/_{s^2}$

FIGURE 2. Screen capture of the expert animated-narrated video solution to problem 1-1. The complete solution can be viewed at https://youtu.be/V6YYWug3Lt8.

The narrated-animated solution was designed to conform to multi-media learning principles (Mayer, 2011; Mayer & Moreno, 2003). For example, we avoided reading text that was presented on the screen since this causes interference between people's visual and aural channels. In addition, we aimed to reduce students' memory load by animating the algebraic steps as we discussed manipulating equations. The animated-narrated solution lasted only five minutes and 18 seconds and students were free to stop it at any point, back up, or replay any segment.

The two problems on the post-test related to problem 1-1 are shown in Figure 3. Problem 3-1 is computational and isomorphic to the problem in Figure 1, with the answer being -5.5 m/s^2 (or 5.5 m/s^2 in the downward direction). Problem 3-2 is conceptual with the answer being “a” since the tension in the situation depicted in the diagram of problem 3-1 of Figure 3 is less than it would be if the string were pulled with a tension equal to mg. The explanation provided by students in problem 3-2 is intended to disambiguate whether or not a student obtained the correct answer without an understanding of the underlying concepts; or perhaps they carelessly marked the wrong answer but gave an explanation displaying correct conceptual understanding.



3-1: A solid disk of mass M=0.47 kg and radius R=30 cm is free to rotate about an axis through its center, with the axis of the disk supported by the ceiling. String is wound around the rim of the disk and hanging from its other end is a mass, m = 0.3 kg. What is the acceleration of the hanging mass?

3-2: Suppose instead that you remove the hanging mass, and now you grab the string and pull vertically down with a tension equal to mg. How does the angular acceleration of the disk now compare to that in the previous problem?

a. The new angular acceleration is larger than what it was in the previous problem

b. The new angular acceleration is smaller than what it was in the previous problem

c. The new angular acceleration is the same as what it was in the previous problem

Explain your reasoning:

FIGURE 3. Post-test problems. Problem 3-1 is the isomorphic calculation problem. Problem 3-2 is the conceptual question.

It is important to discuss what we mean by problems 1-1 and 3-1 being isomorphic, as stated in the previous paragraph. In this paper, we use the term isomorphic to describe problems that are solved by applying the same physics concepts. In this case both problem 1-1 and 3-1 are solved by applying Newton’s Second Law in linear form ($F_{net} = ma$), Newton’s Second Law in angular form ($\tau = I\alpha$), and the relationship between the linear and angular acceleration ($R\alpha = a$). In the cognitive research literature, these features are referred to as a problem’s “deep structure” (i.e., the major concept(s) used to solve a problem). It has been long-established that experts focus on problems’ deep structure as they begin to ponder a problem’s solution (Chi, Feltovich & Glaser, 1981; Docktor & Mestre, 2014 and references therein). Novices, on the other hand, focus more on the “surface features” of problems, meaning the objects in the problem. It should be noted that, although the deep structure of problems 1-1 and 3-1 are the same (and hence we call them isomorphic), the surface features differ somewhat, and the way that the concepts are applied to the objects in the problem also differ somewhat. Problem 1-1 has one object (the disk) and two strings providing forces; problem 3-1 has two objects (the disk and the hanging mass) and one string providing a force (the strings connecting the pulley to the ceiling are irrelevant in this problem). Further, in problem 1-1 Newton’s Second Law in linear and angular form are both applied to the disk; in problem 3-1, Newton’s Second Law in linear form is applied to the hanging mass and Newton’s Second Law in angular form is applied to the disk about its center of mass (the torque provided by the tension is equal to the disk’s moment of inertia about its center of mass times its angular acceleration). Thus, to a student, the two problems are likely to appear somewhat dissimilar, since focusing on surface features would lead one to view 1-1 as a problem involving one disk and two strings, and 3-1 as a problem involving a disk, a mass and one string. This deep structure versus surface feature difference implies that novices need to be able to view the animated-narrated solution to 1-1 and “translate it” so that it can be applied to the somewhat different situation in 3-1, a task that will likely prove difficult to struggling novices.

III. GRADING PROCEDURE

The student solutions to problems 1-1 and 3-1 were hand-graded by the two authors based on a 3 point scale: If a student had shown very little useful work they received a 0; a 1 was assigned for students who made partial progress (e.g., they only applied Newton's Second Law correctly generating one equation); a 2 was assigned to students who generated the three equations needed to solve the problems but made a mathematical error in generating a numerical answer; a 3 was awarded to a totally correct procedure and answer. Whenever the two authors disagreed on a student's score, the two authors met to reach consensus on the student's grade. After grading was completed, all scores of 0 or 1 were combined into a single category called "incorrect" and all scores of 2 or 3 were combined into a single category called "correct". In problem 3-2, we assigned a grade of "correct" if a student selected answer "a" and incorrect if they selected "b" or "c". The explanation to problem 3-2 was also independently graded the two authors on the basis of correct/incorrect; if the authors disagreed on a student's score on the explanation to the answer to problem 3-2, they met to reach consensus. All of the questions were scored by both authors with an initial 96% agreement. Following discussion 100% agreement was reached.

IV. RESULTS

The results for students' performance on problems 1-1, 3-1, 3-2 and their explanation to 3-2, are provided in Table I.

TABLEI. Percentage of students who correctly solved the problems in Figures 1 & 3.

Problem 1-1 Correct/Total (%)	Problem 3-1 Correct/Total (%)	Problem 3-2 Correct/Total (%)	Problem 3-2 Explanation Correct/Total (%)
4/30 (13.3%)	16/68 (23.5%)	10/68 (14.7%)	3/68 (4.4%)

Note: Due to the design of the larger study only 30 individuals attempted Problem 1-1.

Note the following features of the data presented in Table I:

- *Performance on problem 1-1 from the pre-test was at floor-level.* Only 4 students out of the 30 (or 13.3%) who attempted problem 1-1 correctly solved the problem before viewing the solution video. This is a very low percentage but it is not surprising in view of the following: a) The problem was difficult, as noted earlier, b) the students in the study were students that had been invited to participate because they were struggling in the course, and c) there is research that indicates that students do most of their studying for exams at the last minute (that is, they use a cramming strategy—see Blasiman, Dunlosky, & Rawson, 2017; Hartwig & Dunlosky, 2012) and the study was conducted three to five days before the course exam was given. Given that this performance showed that student knew next-to-nothing about solving this problem, there was a lot of room for improvement by learning from the animated-narrated solution, and later showing their learning by solving problems 3-1, 3-2 and providing a correct explanation to 3-2.
- *Very few students were able to generate a correct answer to problem 3-1 after viewing the animated-narrated solution.* Only 23.5% (16 out of 68) of the students who viewed the animated-narrated solution to problem 1-1 to were able to score a 2 or 3 when solving for the acceleration of the hanging mass in problem 3-1. Thus, there was little learning from viewing the animated-narrated solution—students were not able to transfer the deep structure from the solution of an isomorphic problem (problem 1-1) to the new context of problem 3-1, which contained different surface features. This is perhaps not surprising for several reasons: a) The students in this study consisted of struggling students who were having difficulties performing well in midterm exams, b) Transfer of learning has been known to be difficult to achieve (Mestre, 2005), and as discussed earlier, the two problems (1-1 and 3-1) are isomorphic in their deep structure, but not in their surface features, c) Problems 1-1 and 3-1 are difficult for introductory physics students since they involve the application more than one physics concept as well as solving three simultaneous equations for the linear acceleration, and d) The study was conducted three to five days before the midterm exam that tested for this material, and given the cramming strategy that is typically used by students, the only "studying" that had likely taken place prior to this study was the approximately 5 minutes and 18 seconds that it took to view/study the animated-narrated solution, which is not enough to remedy any weaknesses that they may have. We say "approximately" in the previous sentence since

some students spent longer, stopping and re-viewing the animated-narrated solution, and some spent less than the five minutes 18 seconds; the average time spent on the animated-narrated solution by students was four minutes and 47 seconds (59% viewed entire solution, 22% viewed less than half of the solution).

- *Only three students were able to correctly explain why the angular acceleration in problem 3-2 was larger than in problem 3-1.* Note that although 10 students answered the multiple-choice question correctly in 3-2 (i.e., answered that the new angular acceleration if the string is pulled with tension mg is larger than in problem 3-1), only 3 of these 10 students provided a correct explanation. Thus, in the aggregate, only 3 out of 68 (or 4%) understand that pulling the string with a force equal to mg results in a larger angular acceleration of the disk than simply hanging a mass m from the string. One of the three students who provided a correct explanation was among those getting problem 3-1 correct. Thus, showing ability to solve a fairly complicated calculation-based problem (3-1) provides absolutely no indication of understanding conceptually what is going on in the problem they just solved!
- *While most students did not solve problem 3-1 correctly, there is evidence that students attempted to apply concepts from the videos.* As shown in Figure 4, 80% of students earned a score of 0 for problem 1-1, while only 50% scored 0 for problem 3-1. Thus, a number of students did improve their score, indicating a developing understanding of how to approach solving problem 3-1 even if they were not able to completely solve a difficult calculation-based problem. However, we did see evidence of students transferring surface features from the solution videos that did not apply to solving problem 3-1 (negative transfer). In their solutions for problem 3-1, 13 out of 68 students (or 19%) attempted to incorporate the tension on the strings between the ceiling and the disk.

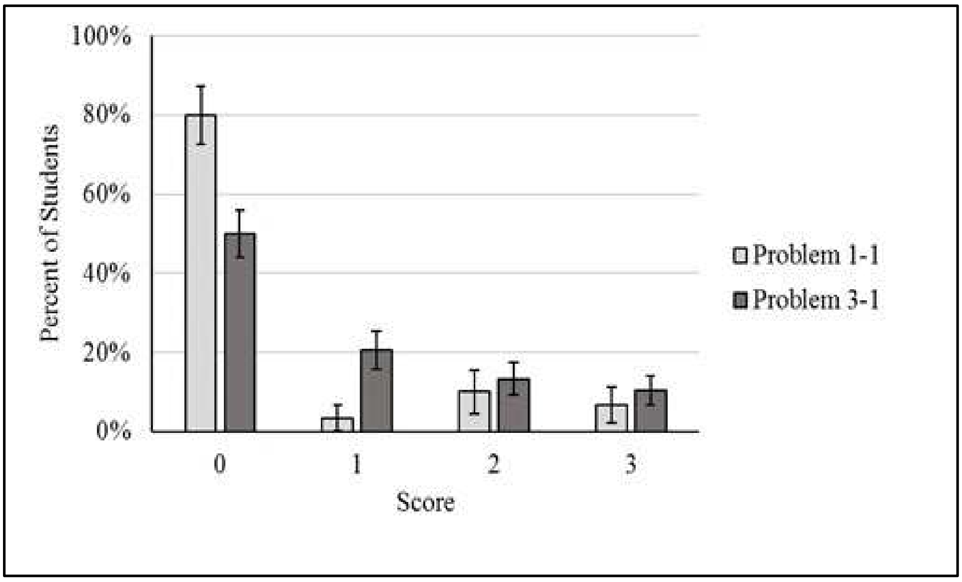


FIGURE 4. Percentage of students with each score on problems 1-1 and 3-1.

The results for students' answers to the multiple-choice question in problem 3-2 based on their performance on problem 3-1 are provided in Table II, while the explanations provided for problem 3-2 if the multiple-choice question was answered correctly is provided in Table III.

TABLE II. Answer Choices for Problem 3-2

	If 3-1 was correct	If 3-1 was incorrect
Answer Choice	**N (%)**	**N (%)**
a) Angular acceleration increases	4 (25.0%)	6 (11.5%)
b) Angular acceleration decreases	1 (6.2%)	2 (3.8%)
c) Angular acceleration is the same	11 (68.8%)	42 (80.8%)
No answer	0 (0.0%)	2 (3.8%)

Note: Percentages may not add to 100% due to rounding.

TABLE III. Explanations for Problem 3-2 if Multiple-Choice Correct

Explanation Category	N (%)	Examples
No explanation given	2 (20.0%)	
Same force/tension	2 (20.0%)	“Your [sic] applying a force equal to mg so they are essentially the same.” “The tension created by you and the hanging mass is both mg. However, in the case of the hand pulling the string there is no (*-ma*) factor, so $I\alpha$ is greater.” “Since there is now no mass that acts on the string, the denominator is smaller, and the value is larger.”
Other explanation	2 (20.0%)	“Tension down is now greater. Mg with m=0.47 is greater than tension when m=0.3 kg. This will cause the disk to spin faster, and so the angular acceleration will be greater. The τ is greater.” “Since there is now no mass that acts on the string, the denominator is smaller, and the value is larger.”
Extra force in new scenario	1 (10.0%)	“Added force will cause the α to be larger, since now the problem involves gravity and added force.”
Larger force needed to have tension of mg (correct explanation)	3 (30.0%)	“Angular acceleration is $\alpha = \frac{rF}{I}$.I and r will stay the same. Before, we had to find F to be $mg - T = ma$ so T is $mg - ma$. We increase F by just pulling with a tension down of mg because $T = mg$ not $T = mg - ma$” “ $F \times r = I\alpha$,$\alpha = \frac{F\times r}{I}$[Same r and I] Relies on tension. $T = mg$. $T = x < mg$ for other problem” “ $\tau = R \times F$and $\alpha = \frac{\tau}{I}$. τ depends on Radius and Force, I depends on Radius and mass, Bigger F = bigger α”

Note the following features of the data presented in these two Tables:

- *Students who answered problem 3-1 correctly were not more likely to answer problem 3-2 correctly.* Most students incorrectly indicated that pulling with a tension of mg resulted in the same acceleration as the hanging block with mass of m regardless of whether they answered problem 3-1 correctly. Only 4 of the 16 students who correctly answered problem 3-1 indicated that the acceleration would increase. A similar percentage of students who incorrectly answered problem 3-1 indicated that the acceleration would increase (6 out of 52).
- *Of the students who selected either “b” or “c” for problem 3-2, 93% incorrectly explained that pulling with a tension of mg resulted in the same (or decreased) acceleration as the hanging block with mass of m, because the same force or tension was applied in both cases.* Alternatively, students who correctly answered “a” for problem 3-2 were more diverse in their explanations. Thirty percent of these students correctly explained that a larger force is needed to have a tension of mg. Alternatively, half of these students were either not able to provide an explanation or gave an explanation that contradicted their choice (i.e., the same force or tension in both scenarios). The remaining three students incorrectly indicated that in problem 3-2 there was an additional force or a change in mass.

V. DISCUSION

As noted above, assessing conceptual understanding in introductory physics courses remains an elusive goal. Some instructors assume that the ability to solve difficult, calculation-based physics problems is reflective of an underlying conceptual understanding. In this study, there was no difference in performance on problem 3-2 (either the multiple choice or the explanation) between students who correctly solved problem 3-1 and those who didn’t. This demonstrates that the ability to solve a difficult calculation-based problem was not indicative of the underlying conceptual understanding of the scenario. The lack of a correlation between the ability to solve the calculation and the conceptual problem suggests that for struggling novice students, calculation-based problem solving and conceptual understanding are unrelated. We conjecture that perhaps there is a stronger correlation between problem solving and conceptual understanding for high-performing physics novices.

Another type of question that aims at assessing students' conceptual understanding are multiple-choice questions that ask students to consider the effect of a change to a scenario. The assumption underlying this type of question is that if students have developed a conceptual understanding, they can correctly select the right effect. Similarly, the ability to answer the multiple-choice conceptual question correctly was not indicative of the underlying conceptual understanding of the scenario given that only 3 out of 10 individuals who answered the multiple-choice question correctly were able to provide a correct explanation to justify their answer. Nevertheless, students' answer to the multiple-choice question together with the explanation provided could identify students who had an incomplete conceptual understanding. Students who assumed that the tension in the string attached to the hanging mass was mg when solving problem 3-1, tended to indicate, in problem 3-2, that they thought that pulling with a tension equal to mg would not affect the angular acceleration of the disk. For these students, their answer to the multiple-choice conceptual question was consistent with the conceptual error they made in the calculation problem.

Given that the calculation problems in this study were difficult, it is reasonable to be skeptical about the potential learning gains from a single five-minute solution video aimed at highlighting the solution steps needed to solve problem 1-1. Indeed, we observed in this study that the number of students who viewed the video solution to problem 1-1 and later solved 3-1 correctly (or who only made a minor mathematical error) increased by only about 10 percentage points. While we didn't see a large increase in the percentage of correct solutions, we did find a shift in student reasoning. After students viewed the five-minute solution video we noted a 30-percentage point decrease in the number of solutions that were scored zero points. The decrease was due to a decline in the number of students who made very little progress. After viewing the solution video more students wrote down both forms of Newton's Second Law, even though they often struggled at applying them appropriately or combining them to solve the problem. In addition, we noticed evidence of negative transfer of surface features from the solution video to the solutions for problem 3-1. In problem 1-1 the tension of the string connected to the wall is important, while in problem 3-1 the tension in the strings connected to the ceiling are not consequential to the acceleration of the block. The observed negative transfer is consistent with prior research that found that novices tend to pay attention to the surface features of problems rather than the deep structure (Chi, et al., 1981; Docktor & Mestre, 2014). This suggests that instruction that points out both the relevance as well as the irrelevance of particular surface features may be beneficial, especially for struggling students.

The elusiveness of conceptual understanding in physics among novices has been observed in other contexts. For example, Kryjevskaia, Stetzer & Le (2014) asked beginning students in a midterm exam a question regarding a 10 kg block on a horizontal surface having coefficient of static friction equal to μ_s=0.4 that was pulled with an applied horizontal force of 30N yet remained at rest. They were asked to compare the magnitudes of the applied and frictional forces. Over 80% of students were able to answer correctly that the magnitude of the two forces was equal. However, a follow-up question asked students to compare the frictional force in the previous problem to a situation identical to it, but with the coefficient of friction now being μ_s=0.6. Performance dropped by 20%, with those answering incorrectly now stating that the frictional force was larger than in the previous problem. Note that in this example both problems are conceptual, yet in the follow-up problem 20% of students abandoned their correct analysis (applying Newton's Second Law) in the original problem in favor of some other, erroneous approach (likely relying on the equation for the maximum static frictional force, $F_s=\mu_s N=\mu_s mg$, which does not apply to the problem as asked).

What are some instructional implications of this study? In introductory physics, we tend to focus on teaching problem solving skills. Even though instructors do discuss physics concepts during the course of instruction, homework problems and exams typically focus on displaying proficiency in solving physics problems. This focus likely sends the message to students that computational prowess is the goal of learning physics. We agree that problem solving and computational prowess are important skills to teach students in physics, but understanding how concepts play out in physical situations is equally important, and we would argue that this important skill is not taught or evaluated explicitly in most physics courses. The erroneous belief that the tension in a string from which a block of mass m hangs is mg under any circumstance, which is only correct if the block does not accelerate, has been commonly observed in previous studies (Mestre, 2002; Feil & Mestre, 2010). This would offer an opportunity to use the scenario in problem 3-1 to help students understand that the assumption leads to a major contradiction, namely that if the tension is mg, the tension and gravitational forces balance, making the resultant force zero, meaning the block would sit still in midair without accelerating, which is clearly an unphysical result. A similar approach could be used in the example from the Kryjevskaia et al. study discussed in the previous paragraph. Challenging students with these types of conceptual questions that do not require computation during the course of instruction would help to develop conceptual understanding alongside of problem solving skills.

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