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Using Computer Simulations with a Real-World Engineering Example to Improve Student Learning of High School Physics: A Case Study of K-12 Engineering Education*

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K-12 engineering education has recently received increasing national and international attention for stimulating interest and improving learning in mathematics and science. This paper describes a case study of K-12 engineering education in which a real-world engineering example is integrated into a computer simulation learning module to improve student understanding of three important concept pairs in high school physics, specifically, in Newtonian mechanics. The three concept pairs include: linear displacement vs. angular displacement, linear velocity vs. angular velocity, linear acceleration vs. angular acceleration. The module has interactive graphical user interfaces requiring student inputs to promote active learning. A total of fifteen high school students participated in the present study. A pre-test, a post-test, and a questionnaire survey were administrated to assess student perceptions about the three concept pairs as well as student learning gains. The coefficients of reliability (Cronbach's alpha) of the assessment instruments were 0.937 and 0.969, respectively. Students reported positive experiences with the developed computer simulation module, and stated that, via the use of the simulation learning module, they developed a better understanding of the conceptual difference and the mathematical relationship between two concepts in each concept pair. Students achieved an average learning gain of 46.7%–71.4%. Finally, the present study reveals that the three lowest learning gains are all related to angular quantities: angular displacement, angular velocity, and angular acceleration. This implies that more educational efforts should be made to improve student understanding of these angular quantities.

Keywords: K-12 engineering education; real-world engineering examples; computer simulations; student perceptions; physics; student learning gains

1. Introduction

1.1 Widespread interest in promoting and improving K-12 engineering education

In the United States, there is a widespread interest in promoting and improving science, technology, engineering, and mathematics (STEM) education at both undergraduate and K-12 (i.e., elementary and secondary schools) levels, due to the important role of STEM education in the nation's economic health, security, and prosperity. The National Academy of Engineering, the National Research Council, the U.S. Department of Education, and the American Association for the Advancement of Science have recently released a series of reports (such as [1, 2]) calling for infusing engineering education into K-12 course curriculum. One report [1] states that "some five million K-12 students have taken part in formal engineering curricula since the early 1990s," and "K-12 students are also being exposed to engineering in informal settings, such as after-school programs and visits to informal-education institutions, such as museums and science centers." Research evidence also shows that K-12 engineering education not only improves understanding of engineering and technology but also stimulates interest and improves learning in mathematics and science [1].

There is increasing attention on K-12 engineering education not only in the U.S. [3–7], but also internationally [8, 9]. The American Society for Engineering Education [3] and the nationwide "Project Lead the Way" initiative [10] have made significant efforts to infuse engineering and engineering technology knowledge into K-12 education. Various efforts have also been made around the world to develop a long-term sustainable partnership among engineering, engineering technology, and education faculty to train technology teachers for K-12 classrooms [4], and to incorporate engineering concepts and engineering design into a variety of K-12 curricular and extracurricular activities [5–10].

1.2 High school physics

Physics is one of the most important courses in the high school science curriculum. It typically includes Newtonian mechanics, fluid mechanics and thermal physics, electricity and magnetism, waves and

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optics, and atomic and nuclear physics [11, 12]. Physics covers numerous foundational concepts that students must understand in order to succeed in subsequent undergraduate science or engineering curricula. For instance, Newtonian mechanics—the technical content that students usually learn first in their physics course—involves fundamental concepts such as displacement, velocity, acceleration, force, torque or moment, work, energy, power, impulse, momentum, and vibrations, as well as foundational laws and principles such as Newton's laws of motion, the Principle of Work and Energy, the Conservation of Energy, and the Principle of Linear Impulse and Momentum [13].

Extensive evidence from physics education research has shown that the lack of a solid understanding of these fundamental concepts, laws, and principles is one of the main reasons that many high school students perform poorly in physics [14–22]. For example, Chang *et al.* [16] and Clement [20] reported that students have a deep misunderstanding of motion and forces. Students believed that motion always implies forces, and that velocity is proportional to the applied force [22]. These conceptual misunderstandings, also called alternative frameworks or children science [23], are difficult to change and are constantly reflected in the students' mathematical formulation of physics problems [18, 21]. A variety of assessment instruments, such as Force Concept Inventory [13] and Mechanics Baseline Test [24], have been developed to diagnose student misconceptions of the most fundamental Newtonian mechanics concepts.

1.3 Computer simulations

Innovative instructional strategies, such as in-class demonstrations, multimedia, wireless communication technologies, and computer simulations, have been widely adopted to improve student understanding of engineering and science (including physics) concepts [25–31]. Educational research [32–34] has demonstrated the effectiveness of these instructional strategies, particularly computer simulations, in improving student learning. Maria and Romuald [33] stated that "computer simulation enables students to model and study physical phenomena in a situation when it is impossible to carry out research, for example, because of time, safety requirements or lack of proper instruments." More important, from the education psychology viewpoint, computer simulations "create an atmosphere in which students may initiate actions, learn how to be more independent, analyze and make conclusions." [33] Through carefully-designed educational experiments that included control and experimental groups in secondary school physics classes, Maria and Romuald [33] found that computer simulations improved student understanding of physical phenomena as well as analytical and creative thinking skills.

Zacharias and Anderson [34] studied the effects of computer simulations on student conceptual understanding of physics, specifically mechanics, waves/optics, and thermal physics. They presented computer simulations to the students prior to performing laboratory experiments. Through pre-post conceptual tests and semi-structured interviews, Zacharias and Anderson [34] found that computer simulations helped students predict and explain the physical phenomena in subsequent laboratory experiments, and that computer simulations fostered a significant conceptual change in relevant physics content areas.

1.4 Objectives and uniqueness of the present study

It must be pointed out that nearly all exiting physics education efforts (e.g., 14–22 and 31–35) focus on improving student understanding of individual concepts, but not concept pairs. The term "concept pair" was first proposed in a recent study [35] on improving student conceptual understanding in an undergraduate engineering dynamics course. According to the definition by Fang [35], a concept pair is a pair of physics concepts that are fundamentally different but closely related.

For example, linear acceleration and angular acceleration is a concept pair. Linear acceleration, in units of m/s^2, is used to quantify the change of linear velocity (m/s) with time. Angular acceleration, in units of rad/s^2, is used to quantify the change of angular velocity (rad/s) with time. There exists a quantitative mathematical relationship between linear (tangential) acceleration and angular acceleration. Without understanding the fundamental difference and relation between the two concepts of a concept pair, students cannot select the correct concept required to accurately interpret a particular physics phenomenon or to solve a particular physics problem. In other words, students will not know when and why to apply each concept and its associated equations to solve physics problems.

The overall goal of the present study is to develop and assess a unique computer simulation learning module to improve student understanding of three important concept pairs in high school Newtonian mechanics. These three concept pairs are: linear displacement vs. angular displacement, linear velocity vs. angular velocity, linear acceleration vs. angular acceleration. The computer simulation learning module developed from the present study was implemented in a high school physics course.

The developed computer simulation learning module is unique and combines three features. First, a real-world engineering example is integrated into computer simulations to make student learning relevant and meaningful. Real-world applications also stimulate and motivate student learning [1, 2, 36–38]. As McClure [39] pointed out, "showing real-world connections and involving students in activities that inspire creative applications are strategies grounded in both constructivist theory and theories of motivational design." Second, mathematical calculations are integrated into computer simulations in the present study, so students can connect physics concepts with mathematical equations to understand each concept pair in greater depth. Most of existing computer simulations developed for high school and college physics use graphs and curves to show students physical phenomena but fail to show the mathematics behind physical phenomena. Third, computer simulations developed from the present study are interactive and require student inputs to promote active learning. Active learning is widely regarded as one of the most effective learning strategies [31, 40]. When students use the computer simulation learning module developed from the present study, students can make a change in inputs and then immediately see how outputs are simultaneously affected.

The authors of this paper have performed an extensive literature review using a variety of popular databases, such as the Education Resources Information Center, Science Citation Index, Social Science Citation Index, Engineering Citation Index, Academic Search Premier, the ASEE annual conference proceedings (1995–2011), and the ASEE/IEEE Frontier in Education conference proceedings (1995–2011). The results of this literature review show that none of the existing studies combine the above-stated three features in one computer simulation module.

1.5 Assessment questions of the present study

The present study has the following three assessment questions:

1. To what extent did students change their perceptions about the three concept pairs addressed in the present study after students learned from the developed computer simulation learning module?
2. To what extent did student learn from the developed computer simulation learning module?
3. What were student attitudes towards and experiences with the developed computer simulation learning module?

1.6 Logic structure of this paper

This paper first describes the real-world engineering example selected for use in the computer simulation learning module. Then, the graphical user interfaces (GUIs) of the simulation learning module are described in detail. Next, the assessment method is introduced, including participants, data collection procedure, pre-test and post-test, reliability and validity of assessment instruments, and questionnaire survey. The results are presented and analyzed. Finally, the answers to the three assessment questions and educational implications are summarized at the end of the paper.

2. A real-world engineering example

The selection of appropriate engineering examples is important to stimulate student motivation to learn science and mathematics [1, 36–38]. The first author of this paper has nearly 30 years of engineering experience with emphasis in the area of metal machining. Therefore, a real-world engineering example that involves the process of metal machining, as shown in Fig. 1, was selected for use in the computer simulation learning module.

This Flash video clip was developed from the author's machining research laboratory. It illustrates the rotational motion of a cylindrical workpiece that is being machined by a cutting tool insert. Fundamental physics concepts—displacement, velocity, and acceleration—are addressed in this engineering example. Students could watch the online video clip (with audio) to understand the engineering context in which the computer simulation module was developed.

3. Computer simulation learning module

The simulation learning module contains eight interactive graphical user interfaces (GUIs), as shown in Fig. 2. Figures 3–6 show the four most

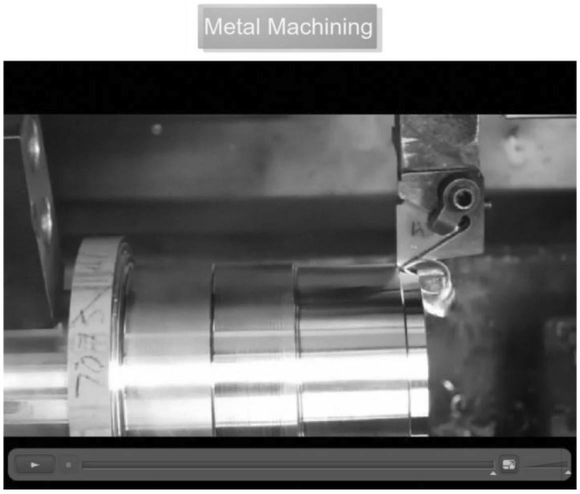
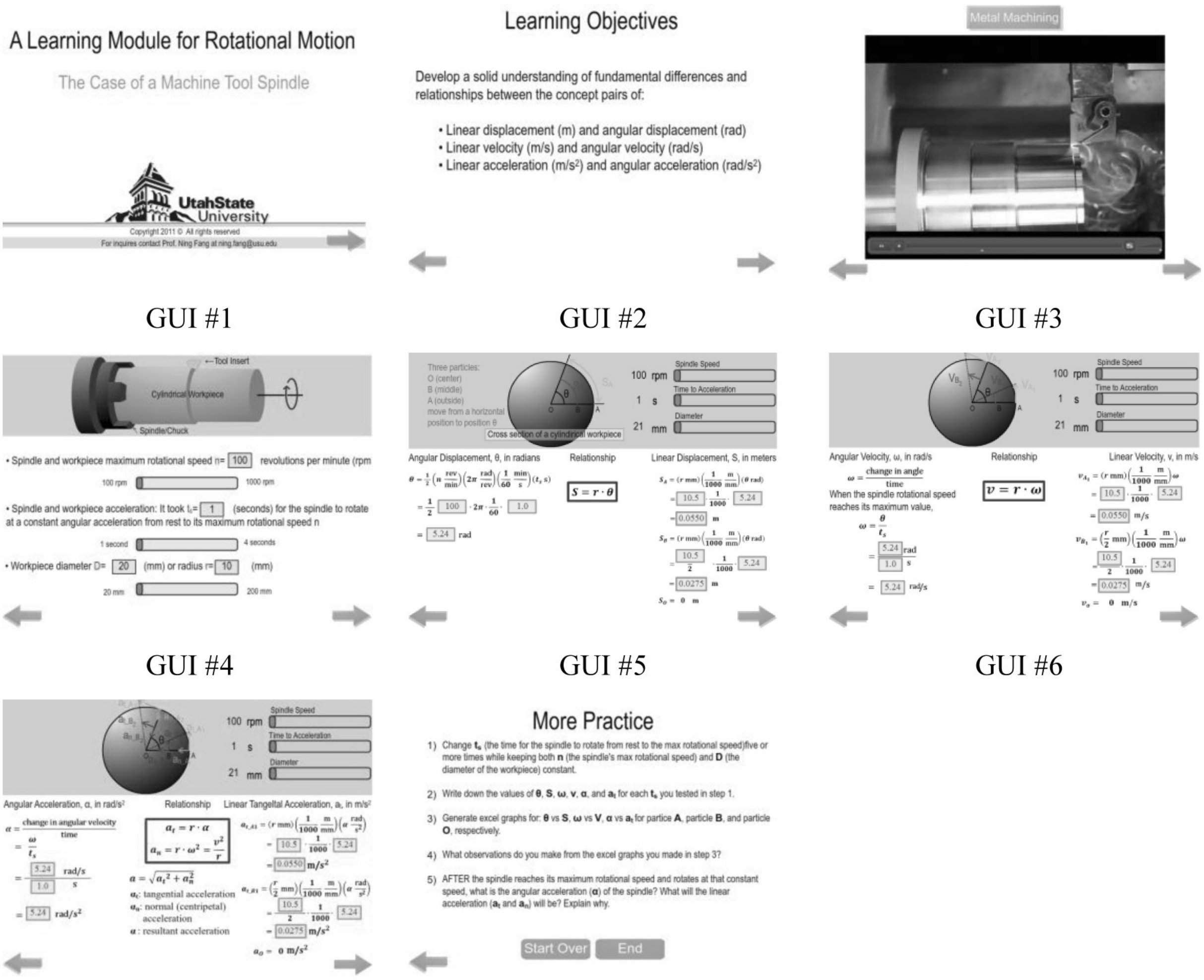


Fig. 1. A Flash video clip that shows the process of metal machining.



GUI #1

A Learning Module for Rotational Motion

The Case of a Machine Tool Spindle

UtahState University

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For inquires contact Prof. Ning Fang at ning.fang@usu.edu

GUI #2

Learning Objectives

Develop a solid understanding of fundamental differences and relationships between the concept pairs of:

- Linear displacement (m) and angular displacement (rad)
- Linear velocity (m/s) and angular velocity (rad/s)
- Linear acceleration (m/s^2) and angular acceleration (rad/s^2)

GUI #3

GUI #4

• Spindle and workpiece maximum rotational speed n= 100 revolutions per minute (rpm

100 rpm — 1000 rpm

• Spindle and workpiece acceleration: It took t_s= 1 (seconds) for the spindle to rotate at a constant angular acceleration from rest to its maximum rotational speed n

1 second — 4 seconds

• Workpiece diameter D= 20 (mm) or radius r= 10 (mm)

20 mm — 200 mm

GUI #5

Three particles:
O (center)
B (middle)
A (outside)
move from a horizontal position to position θ

Cross section of a cylindrical workpiece

Spindle Speed: 100 rpm

Time to Acceleration: 1 s

Diameter: 21 mm

Angular Displacement, θ, in radians

$$\theta = \frac{1}{2}\left(n\,\frac{\text{rev}}{\text{min}}\right)\left(2\pi\,\frac{\text{rad}}{\text{rev}}\right)\left(\frac{1}{60}\,\frac{\text{min}}{\text{s}}\right)(t_s\ \text{s})$$

$$= \frac{1}{2}\cdot \boxed{100} \cdot 2\pi \cdot \frac{1}{60} \cdot \boxed{1.0}$$

$$= \boxed{5.24}\ \text{rad}$$

Relationship

$$\boxed{S = r\cdot\theta}$$

Linear Displacement, S, in meters

$$S_A = (r\ \text{mm})\left(\frac{1}{1000}\,\frac{\text{m}}{\text{mm}}\right)(\theta\ \text{rad})$$

$$= \boxed{10.5}\cdot\frac{1}{1000}\cdot\boxed{5.24}$$

$$= \boxed{0.0550}\ \text{m}$$

$$S_B = (r\ \text{mm})\left(\frac{1}{1000}\,\frac{\text{m}}{\text{mm}}\right)(\theta\ \text{rad})$$

$$= \frac{\boxed{10.5}}{2}\cdot\frac{1}{1000}\cdot\boxed{5.24}$$

$$= \boxed{0.0275}\ \text{m}$$

$$S_O = 0\ \text{m}$$

GUI #6

Spindle Speed: 100 rpm

Time to Acceleration: 1 s

Diameter: 21 mm

Angular Velocity, ω, in rad/s

$$\omega = \frac{\text{change in angle}}{\text{time}}$$

When the spindle rotational speed reaches its maximum value,

$$\omega = \frac{\theta}{t_s}$$

$$= \frac{\boxed{5.24}\ \text{rad}}{\boxed{1.0}\ \text{s}}$$

$$= \boxed{5.24}\ \text{rad/s}$$

Relationship

$$\boxed{v = r\cdot\omega}$$

Linear Velocity, v, in m/s

$$v_{A_1} = (r\ \text{mm})\left(\frac{1}{1000}\,\frac{\text{m}}{\text{mm}}\right)\omega$$

$$= \boxed{10.5}\cdot\frac{1}{1000}\cdot\boxed{5.24}$$

$$= \boxed{0.0550}\ \text{m/s}$$

$$v_{B_1} = \left(\frac{r}{2}\ \text{mm}\right)\left(\frac{1}{1000}\,\frac{\text{m}}{\text{mm}}\right)\omega$$

$$= \frac{\boxed{10.5}}{2}\cdot\frac{1}{1000}\cdot\boxed{5.24}$$

$$= \boxed{0.0275}\ \text{m/s}$$

$$v_o = 0\ \text{m/s}$$

GUI #7

Spindle Speed: 100 rpm

Time to Acceleration: 1 s

Diameter: 21 mm

Angular Acceleration, α, in rad/s^2

$$\alpha = \frac{\text{change in angular velocity}}{\text{time}}$$

$$= \frac{\omega}{t_s}$$

$$= \frac{\boxed{5.24}\ \text{rad/s}}{\boxed{1.0}\ \text{s}}$$

$$= \boxed{5.24}\ \text{rad/s}^2$$

Relationship

$$\boxed{\begin{aligned} a_t &= r\cdot\alpha \\ a_n &= r\cdot\omega^2 = \frac{v^2}{r} \end{aligned}}$$

$$a = \sqrt{a_t{}^2 + a_n^2}$$

a_t: tangential acceleration

a_n: normal (centripetal) acceleration

a : resultant acceleration

Linear Tangeltal Acceleration, a_t, in m/s^2

$$a_{t\_A1} = (r\ \text{mm})\left(\frac{1}{1000}\,\frac{\text{m}}{\text{mm}}\right)\left(\alpha\,\frac{\text{rad}}{\text{s}^2}\right)$$

$$= \boxed{10.5}\cdot\frac{1}{1000}\cdot\boxed{5.24}$$

$$= \boxed{0.0550}\ \text{m/s}^2$$

$$a_{t\_B1} = \left(\frac{r}{2}\ \text{mm}\right)\left(\frac{1}{1000}\,\frac{\text{m}}{\text{mm}}\right)\left(\alpha\,\frac{\text{rad}}{\text{s}^2}\right)$$

$$= \frac{\boxed{10.5}}{2}\cdot\frac{1}{1000}\cdot\boxed{5.24}$$

$$= \boxed{0.0275}\ \text{m/s}^2$$

$$a_O = 0\ \text{m/s}^2$$

GUI #8

More Practice

1) Change t_s (the time for the spindle to rotate from rest to the max rotational speed)five or more times while keeping both **n** (the spindle's max rotational speed) and **D** (the diameter of the workpiece) constant.

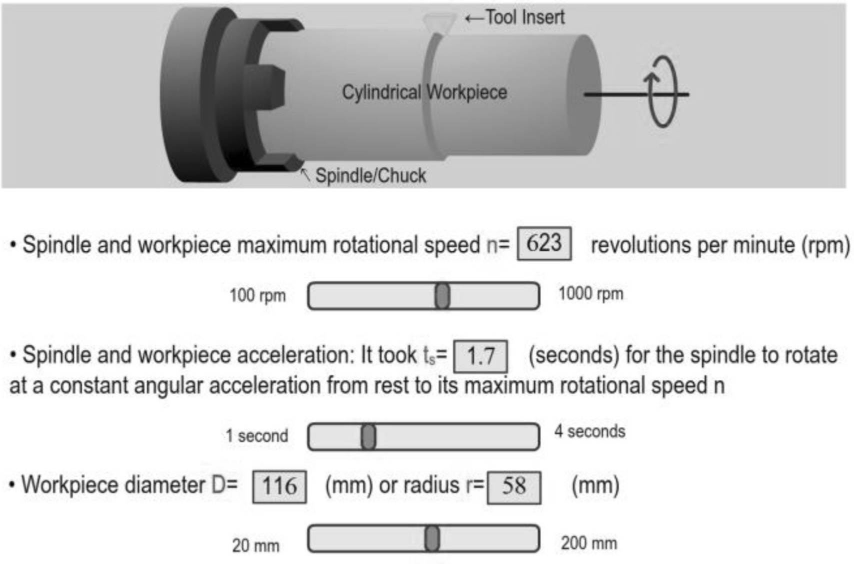
2) Write down the values of **θ**, **S**, **ω**, **v**, **α**, and a_t for each t_s you tested in step 1.

3) Generate excel graphs for: **θ** vs **S**, **ω** vs **V**, **α** vs a_t for partice **A**, particle **B**, and particle **O**, respectively.

4) What observations do you make from the excel graphs you made in step 3?

5) AFTER the spindle reaches its maximum rotational speed and rotates at that constant speed, what is the angular acceleration (**α**) of the spindle? What will the linear acceleration (a_t and a_n) will be? Explain why.

Fig. 2. Graphical User Interfaces (GUIs) of the simulation learning module.



• Spindle and workpiece maximum rotational speed n= 623 revolutions per minute (rpm)

100 rpm — 1000 rpm

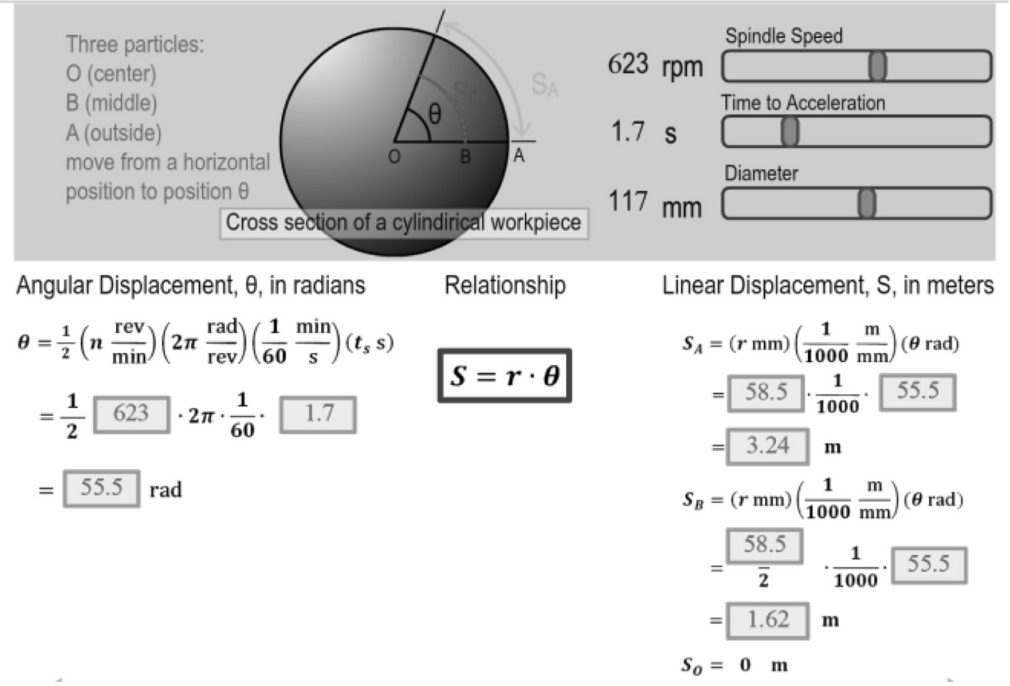
• Spindle and workpiece acceleration: It took t_s= 1.7 (seconds) for the spindle to rotate at a constant angular acceleration from rest to its maximum rotational speed n

1 second — 4 seconds

• Workpiece diameter D= 116 (mm) or radius r= 58 (mm)

20 mm — 200 mm

Fig. 3. The simulation learning module GUI #4.



Three particles:
O (center)
B (middle)
A (outside)
move from a horizontal position to position θ

Cross section of a cylindirical workpiece

Spindle Speed 623 rpm

Time to Acceleration 1.7 s

Diameter 117 mm

Angular Displacement, θ, in radians

$$\theta = \frac{1}{2}\left(n\ \frac{\text{rev}}{\text{min}}\right)\left(2\pi\ \frac{\text{rad}}{\text{rev}}\right)\left(\frac{1}{60}\ \frac{\text{min}}{\text{s}}\right)(t_s\ \text{s})$$
$$= \frac{1}{2}\ \boxed{623}\cdot 2\pi\cdot\frac{1}{60}\cdot\ \boxed{1.7}$$
$$= \boxed{55.5}\ \text{rad}$$

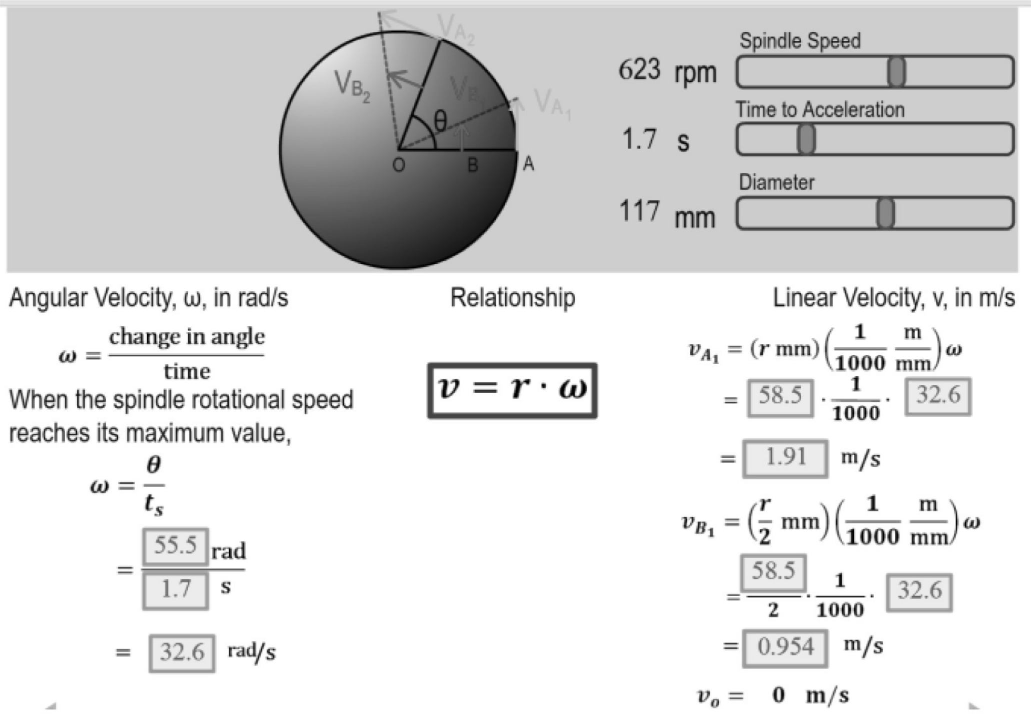
Relationship

$$\boxed{S = r\cdot\theta}$$

Linear Displacement, S, in meters

$$S_A = (r\ \text{mm})\left(\frac{1}{1000}\ \frac{\text{m}}{\text{mm}}\right)(\theta\ \text{rad})$$
$$= \boxed{58.5}\cdot\frac{1}{1000}\cdot\ \boxed{55.5}$$
$$= \boxed{3.24}\ \text{m}$$
$$S_B = (r\ \text{mm})\left(\frac{1}{1000}\ \frac{\text{m}}{\text{mm}}\right)(\theta\ \text{rad})$$
$$= \frac{\boxed{58.5}}{2}\cdot\frac{1}{1000}\cdot\ \boxed{55.5}$$
$$= \boxed{1.62}\ \text{m}$$
$$S_O = 0\ \text{m}$$

Fig. 4. The simulation learning module GUI #5.



Spindle Speed 623 rpm

Time to Acceleration 1.7 s

Diameter 117 mm

Angular Velocity, ω, in rad/s

$$\omega = \frac{\text{change in angle}}{\text{time}}$$

When the spindle rotational speed reaches its maximum value,

$$\omega = \frac{\theta}{t_s}$$
$$= \frac{\boxed{55.5}\ \text{rad}}{\boxed{1.7}\ \text{s}}$$
$$= \boxed{32.6}\ \text{rad/s}$$

Relationship

$$\boxed{v = r\cdot\omega}$$

Linear Velocity, v, in m/s

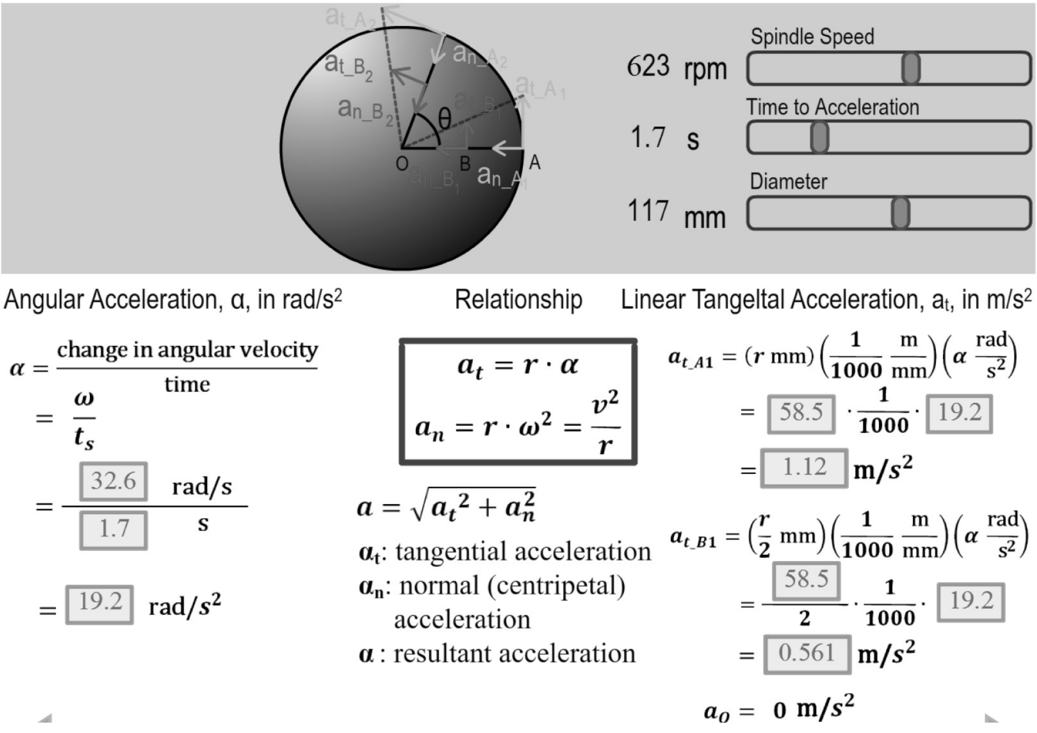
$$v_{A_1} = (r\ \text{mm})\left(\frac{1}{1000}\ \frac{\text{m}}{\text{mm}}\right)\omega$$
$$= \boxed{58.5}\cdot\frac{1}{1000}\cdot\ \boxed{32.6}$$
$$= \boxed{1.91}\ \text{m/s}$$
$$v_{B_1} = \left(\frac{r}{2}\ \text{mm}\right)\left(\frac{1}{1000}\ \frac{\text{m}}{\text{mm}}\right)\omega$$
$$= \frac{\boxed{58.5}}{2}\cdot\frac{1}{1000}\cdot\ \boxed{32.6}$$
$$= \boxed{0.954}\ \text{m/s}$$
$$v_o = 0\ \text{m/s}$$

Fig. 5. The simulation learning module GUI #6.

important GUIs where students learn the concepts of displacement, velocity, and acceleration and learn how to perform relevant calculations (i.e., developing a quantitative solution to relevant problems).

The learning objective of the simulation module is provided on GUI #2, that is, for students to develop a solid understanding of fundamental differences and relationships between the concept pairs of:

- linear displacement (m) vs. angular displacement (rad);



Spindle Speed
623 rpm

Time to Acceleration
1.7 s

Diameter
117 mm

Angular Acceleration, α, in rad/s²

$$\alpha = \frac{\text{change in angular velocity}}{\text{time}} = \frac{\omega}{t_s} = \frac{\boxed{32.6}\ \text{rad/s}}{\boxed{1.7}\ \text{s}} = \boxed{19.2}\ \text{rad}/s^2$$

Relationship

$$\boxed{\begin{aligned} a_t &= r \cdot \alpha \\ a_n &= r \cdot \omega^2 = \frac{v^2}{r} \end{aligned}}$$

$$a = \sqrt{{a_t}^2 + a_n^2}$$

a_t: tangential acceleration
a_n: normal (centripetal) acceleration
a : resultant acceleration

Linear Tangeltal Acceleration, a_t, in m/s²

$$a_{t\_A1} = (r\ \text{mm})\left(\frac{1}{1000}\,\frac{\text{m}}{\text{mm}}\right)\left(\alpha\,\frac{\text{rad}}{\text{s}^2}\right) = \boxed{58.5} \cdot \frac{1}{1000} \cdot \boxed{19.2} = \boxed{1.12}\ \text{m}/s^2$$

$$a_{t\_B1} = \left(\frac{r}{2}\ \text{mm}\right)\left(\frac{1}{1000}\,\frac{\text{m}}{\text{mm}}\right)\left(\alpha\,\frac{\text{rad}}{\text{s}^2}\right) = \frac{\boxed{58.5}}{2} \cdot \frac{1}{1000} \cdot \boxed{19.2} = \boxed{0.561}\ \text{m}/s^2$$

$$a_O = 0\ \text{m}/s^2$$

Fig. 6. The simulation learning module GUI #7.

- linear velocity (m/s) vs. angular velocity (rad/s);
- linear acceleration (m/s^2) vs. angular acceleration (rad/s^2).

On each GUI, students can move the slider bars (see those shown in Figs 3–6) to change the values of the following three inputs:

1. spindle and workpiece maximum rotational speed n (rpm);
2. the time t_s (seconds) for the spindle to rate at a constant angular acceleration from rest to its maximum rotational speed;
3. workpiece diameter D (mm) or radius r (mm).

The GUIs in Figs 3–6 provide all necessary mathematical equations and show how displacement, velocity, and acceleration simultaneously change when students move the slider bars to change input values. The equations that relate linear displacement to angular displacement ($S = r \cdot \theta$), relate linear velocity to angular velocity ($v = r \cdot \omega$), and relate linear acceleration to angular acceleration ($a_t = r \cdot \alpha$) are boxed and shown in the middle of each GUI in Figs 3–6.

In order to foster deep conceptual understanding as well as critical thinking, students were asked to perform the following tasks on the last GUI (i.e., GUI #8):

1. Change t_s (the time for the spindle to rotate from rest to the max rotational speed) five or more times while keeping both n (the spindle's max rotational speed) and D (the diameter of the workpiece) constant.
2. Write down the values of θ, S, ω, v, α, and a_t for each t_s tested in step 1.
3. Generate Excel graphs for θ vs. S, ω vs. v, α vs. a_t for particle A, particle B, and particle O, respectively.
4. Answer the question: What observations do you make from the Excel graphs you made in step 3?
5. Answer the questions: AFTER the spindle reaches its maximum rotational speed and rotates at that constant speed, what is the angular acceleration (a) of the spindle? What will the linear acceleration (a_t and a_n) will be? Explain why.

4. Assessment method

4.1 Participants

The above-described computer simulation learning module was recently implemented in an eleventh grade high school physics course. The course was taught by the third author of this paper. One of the core objectives of the course is that "student will understand and mathematically manipulate the concepts of motion—position (displacement), velocity, and acceleration." Fifteen students, including nine female and six male students, participated in the present study. All the students (minors) involved and their parents signed the letter of informed consent before the students participated in the study.

4.2 Participants

During the semester, student participants took a pre-test, attended a laboratory session in which the computer simulation module was employed and, three weeks later, took a post-test to assess student learning gains. After the post-test, a questionnaire survey was also administrated to survey student attitudes towards and experiences with the computer simulation learning modules.

4.3 Pre-test and post-test

The pre-test and post-test contained eighteen assessment items that were developed based on the real-world engineering example described above. The first six items, as shown in Table 1, assessed student perceptions of three concept pairs (linear displacement vs. angular displacement, linear velocity vs. angular velocity, and linear acceleration vs. angular acceleration).

The remaining twelve items, as shown in Table 2, assessed students' skills of mathematically manipulating relevant concepts. The following technical problem associated with Table 2 was developed from the previously-described real-world engineering example.

As shown in Fig. 7, particles A and B are on the circumference and the middle, respectively, of a disk. Each particle has a mass of 0.002 kg. The disk has a radius of 100 mm. It takes two seconds, at a constant angular acceleration, for the disk to rotate from rest to the rotational speed of 400 revolutions per minute.

If a student provided a correct answer to an assessment item shown in Table 2, the student earned one point; otherwise the student earned zero points. In cases where a student's answer was incorrect due to the wrong convention of units, partial credit (0.5 points) was given to the student.

After the post-test, the following equation was employed to calculate the learning gain for each student and each assessment item:

$$\text{Leaning gain} = \frac{\text{Post-test score (\%)} - \text{Pre-test score (\%)}}{100\ (\%) - \text{Pre-test score (\%)}} \tag{1}$$

4.4 Reliability and validity of assessment instruments

The assessment instruments shown in Tables 1 and 2 have high reliability. Based on the calculations using a commercial statistical software package SPSS Base (version 20), the coefficients of reliability (Cronbach's alpha) were 0.937 and 0.969 for the six items in Table 1 and the twelve items in Table 2, respectively.

Table 1. The instrument to assess student perceptions

No.	**Statements**	**1**	**2**	**3**	**4**	**5**
1	I understand the conceptual difference between linear displacement and angular displacement.					
2	I understand the mathematical relationship between linear displacement and angular displacement.					
3	I understand the conceptual difference between linear velocity and angular velocity.					
4	I understand the mathematical relationship between linear velocity and angular velocity.					
5	I understand the conceptual difference between linear acceleration and angular acceleration.					
6	I understand the mathematical relationship between linear acceleration and angular acceleration.					

* 1–Strongly disagree, 2–Disagree, 3–Neutral, 4–Agree, 5–Strongly agree.

Table 2. The instrument to assess students' skills of mathematically manipulating relevant concepts

No.	**Problems (fill in blanks)**
7	Over 2 seconds, the linear displacement of particle A is __________ meters.
8	Over 2 seconds, the linear displacement of particle B is __________ meters.
9	Over 2 seconds, the angular displacement of particle A is __________ radians.
10	Over 2 seconds, the angular displacement of particle B is __________ radians.
11	At the end of 2 seconds, the linear velocity of particle A is __________ m/s.
12	At the end of 2 seconds, the linear velocity of particle B is __________ m/s.
13	At the end of 2 seconds, the angular velocity of particle A is __________ rad/s.
14	At the end of 2 seconds, the angular velocity of particle B is __________ rad/s.
15	At the end of 2 seconds, the linear tangential acceleration of particle A is __________ m/s^2.
16	At the end of 2 seconds, the linear tangential acceleration of particle B is __________ m/s^2.
17	At the end of 2 seconds, the angular acceleration of particle A is __________ rad/s^2.
18	At the end of 2 seconds, the angular acceleration of particle B is __________ rad/s^2.

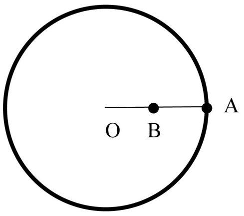


Fig. 7. The technical problem for use in the pre-test and post-test (OA = 100 mm, OB = 50 mm).

Table 3. Change of student perceptions

	Pre-test		Post-test	
Assessment	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
1	2.80	0.94	4.07	0.96
2	2.27	1.10	3.93	0.96
3	2.73	1.03	3.87	1.06
4	2.40	0.74	3.60	1.12
5	2.60	0.91	3.87	0.92
6	2.33	0.82	3.33	1.29

Content validity was employed in the present study as a major measurement of construct validity. The content validity of the assessment instruments shown in Tables 1 and 2 were measured using Lawshe's quantitative method [41]. Five veteran instructors were asked to respond to the following question for each assessment item: "Is the skill or knowledge measured by this item 'essential,' 'useful, but not essential,' or 'not necessary' to the performance of the construct?" The content validity ratio [41] was then calculated based on the responses of these veteran instructors. The results showed that the content validity ratio was nearly 1.0, which confirmed the content validity of the assessment instruments developed in the present study.

4.5 Questionnaire survey

The questionnaire survey that was administrated after the post-test included six open-ended questions that surveyed student attitudes towards and experiences with the computer simulation learning module. Students were asked to provide feedback on the following questions:

1. To what extent did the computer simulation help, or not help, with your understanding of physics concepts?
2. To what extent did the computer simulation help, or not help, with your understanding of mathematical calculations?
3. What part of the simulation module did you like the most?
4. What part of the simulation module did you dislike the most?
5. What part of the simulation module did you learn the most from?
6. What part of the simulation module could be improved?

5. Results and analysis

5.1 Change of student perceptions

Table 3 shows the change of student perceptions of the conceptual difference and the mathematical relationship between each concept pair in the pre-test and post-test. As seen from Table 3, the mean values are 2.33 to 2.88 in the pre-test, and increase to 3.33 to 4.07 in the post-test. In other words, students thought that, via the use of the simulation learning module, they developed a better understanding of the conceptual difference and the mathematical relationship between two concepts in each concept pair.

Note that the highest mean value (4.07) in the post-test corresponds to assessment item No. 1: the understanding of the conceptual difference between linear displacement and angular displacement. The lowest mean value (3.33) in the post-test corresponds to assessment item No. 6: the understanding of the mathematical relationship between linear acceleration and angular acceleration. This lowest mean value (3.33) also has the highest standard deviation (1.29), which implies that students have the most diverse perceptions on assessment item No. 6. This raises a need to modify and refine the design of the simulation learning module to improve student understanding of how linear acceleration and angular acceleration are mathematically related to each other.

5.2 Student leaning gains

The total points that a student earned from all assessment items listed in Table 2 were divided by the total number of assessment items. The resulting scores were used as the test scores (varying between 0.0 and 1.0) and reported in Table 4.

As seen from Table 4, the students scored zero or nearly zero on all assessment items in the pre-test. The learning gains for all students averaged between 46.7% (for assessment item No. 18) and 71.4% (for assessment items Nos. 7 and 8), which confirms the effectiveness of the developed simulation learning module.

Table 4 also shows that the three lowest learning gains are all related to angular quantities: 53.3% for assessment item No. 10 on angular displacement, 50% for assessment item No. 14 on angular velocity), and 46.7% for assessment item No. 18 on angular acceleration. Therefore, there is still much room to modify and refine the design of the simulation learning module to improve student understanding of angular quantities.

Table 4. Student learning gains

Assessment item no.	Pre-test Mean	Pre-test Std. dev.	Post-test Mean	Post-test Std. dev.	Average learning gains (%)
7	0.07	0.26	0.73	0.37	71.4
8	0.07	0.26	0.73	0.37	71.4
9	0	0	0.70	0.41	70.0
10	0	0	0.53	0.48	53.3
11	0	0	0.63	0.40	63.3
12	0	0	0.63	0.40	63.3
13	0	0	0.60	0.39	60.0
14	0	0	0.50	0.42	50.0
15	0	0	0.63	0.40	63.3
16	0	0	0.63	0.40	63.3
17	0	0	0.57	0.42	56.7
18	0	0	0.47	0.44	46.7

5.3 Student attitudes and experiences

In the questionnaire survey, the students reported positive attitudes towards and experiences with the developed computer simulation learning module. Representative student comments (original, without editing) are listed below:

- "The modules illustrated a real-world application for the concepts that helped me see what I was applying the concepts to. Seeing the diagram of each concept was useful in showing how each piece of a formula fits into the big picture."
- "The computer simulation aid helps me understand the physics concepts, because of the preliminary video we viewed, and the adjusting bars of speed, size and rotation. This helped me understand what parts of the equation was being calculated, where to plug them in, and how to solve for the missing variable."
- "I really began to remember from learning MIS previously. But this time, rather than just memorizing formulas, the module really helped me understand the why."
- "I got to see all the numbers right in front of me without screwing up the calculations myself. I went from having no idea what I was doing to being able to predict the effects of changing variables. This helped me to imagine the concepts at work."
- "It showed what values were being put into the equations, which was helpful, and it showed what happens when a value is changing, which helped me understand the relationships between the concepts."
- "The concepts were labeled on the diagrams, which I found helpful. It was much easier to see where things came from once I understood the difference between linear and angular displacements, velocities, and acceleration."
- "The computer modules helped me see how to do the calculations. It was really helpful to see all the steps on one screen, with the formulas at the top of the page."

The computer program included at www.wordle.net was used to generate the "word clouds"

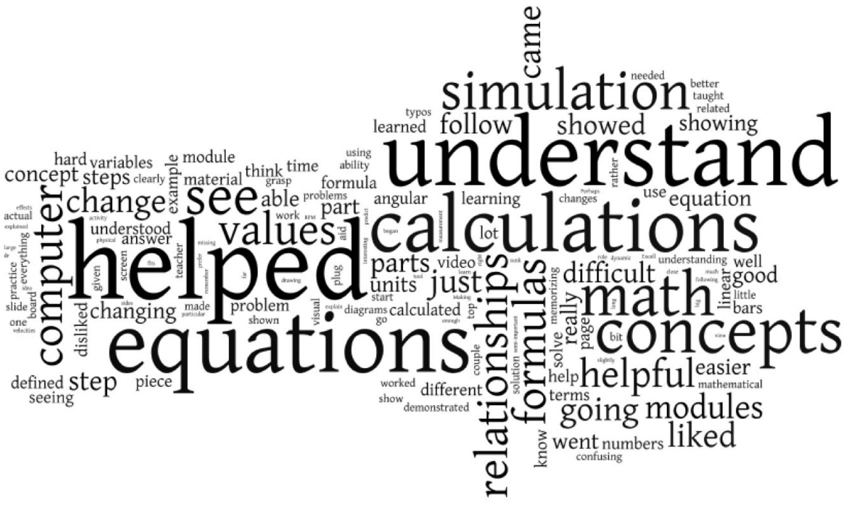


Fig. 8. "Word clouds" generated from student comments.

based on the comments of all fifteen student participants. The resulting "word clouds" were shown in Fig. 8, where the words that appear more frequently from student comments are shown in greater font size. As seen from Fig. 8, the six words most frequently used by students are "helped," "understand," "calculations," "equations," "math," and "concepts."

6. Limitations of this study

This pilot study is limited in two aspects. First, the sample size in the study is limited by the number of students who took physics in InTech Collegiate High School, where data were collected. In the authors' state, physics is not a required course in high school curriculum. As a result, many high school students do not take physics—a historically difficult course that many students try to avoid. Second, this study does not include a comparison group. All students who participated in this study received treatments, i.e., learning from computer simulations. A comparison group will be included in the future expended study.

7. Conclusions

K-12 engineering education has recently received increasing national and international attention for stimulating interest and improving learning in mathematics and science. This paper has described a case study of K-12 engineering education in which a real-world engineering example is integrated into a computer simulation learning module to improve student understanding of three important concept pairs in high school physics, specifically, Newtonian mechanics. Based on the analysis of the results, the answers to the three assessment questions of the present study are as follows:

Assessment question 1: To what extent did students change their perceptions about the three concept pairs addressed in the present study after students learned from the developed computer simulation learning module?

Answer: Students stated that they developed a better understanding of the conceptual difference and the mathematical relationship between two concepts in each concept pair. On a five-point scale (with 1 for the weakest understanding and 5 for the strongest understanding), the mean values of student perceptions were 2.33 to 2.88 in the preset, and increased to 3.33 to 4.07 in the post-test.

Assessment question 2: To what extent did student learn from the developed computer simulation learning module?

Answer: The learning gains for all students averaged between 46.7% and 71.4%. This confirms the effectiveness of the developed simulation learning module.

Assessment question 3: What were student attitudes towards and experiences with the developed computer simulation learning module?

Answer: The students reported positive attitudes towards and experiences with the developed computer simulation learning module. The six words most frequently used by students are "helped," "understand," "calculations," "equations," "math," and "concepts."

Finally, the research from the present study reveals that the three lowest learning gains are all related to angular quantities: angular displacement, angular velocity, and angular acceleration. This implies that more educational efforts should be made to improve student understanding of angular quantities.

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