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Bridging the Gap: Computer Simulations and Video Recordings for Remote Inquiry-Based Laboratory Activities in Mechanics

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ABSTRACT

Based on the pedagogical principle of cognitive conflict, Inquiry-Based Laboratory Activities (IBLAs) have been shown to improve conceptual understanding of challenging science and engineering topics. Yet, providing students physical apparatuses to complete an IBLA is not tenable in every instructional setting. This paper reports design, development, and implementation of two Remote IBLAs in mechanics – the Spool IBLA and the Rolling Cylinder IBLA. The Remote IBLAs were constructed based on successful, analogous Physical IBLAs and contain two elements, a video of the central activity in the Physical IBLA followed by a Virtual Laboratory simulation. The simulation provides students additional vector and graphical representations while the combined video and simulation are designed to manage the learner's cognitive load. A naturalistic preliminary study used a split design to measure student perception and performance in both remote and physical conditions. Students expressed that the combined video and simulation was more effective for their learning than video alone or simulation alone. Students articulated each element had unique merits; the video provided the "what" of the activity - a concrete example of the phenomenon under investigation that concretizes the experiment. The simulation provided information "why" - with the added vector representations giving students the opportunity to develop their mental models by explaining why the underlying phenomenon occurs. When compared to the Physical IBLA, there was not a difference in perceptions of learning nor in measured performance on summative concept inventory questions; however, students reported they were less motivated with one of the Remote IBLA activities.

Key words: Conceptual change, Inquiry based learning, Learning technology

INTRODUCTION

Inquiry-Based Laboratory Activities (IBLAs) have been shown to improve student understanding of difficult concepts in science and engineering (Laws, Sokoloff and Thornton 1999; Prince, Vigeant and Nottis 2016; Self and Widmann 2017). Typically, IBLAs are constructed around brief hands-on experiments designed so that students can confront common misconceptions. In a predict-observe-explain sequence, these activities prompt students to make sense of a phenomenon as they work collaboratively through a guided worksheet. However, IBLAs are commonly developed around physical experiments that present logistical challenges for many instructors, such as those who teach large classes, those with limited resources, or those confined to remote instruction due to the COVID 19 pandemic.

With this study, we describe an alternative instructional design for Remote IBLAs where videos of the physical experiments are used in tandem with computer simulations to replace the hands-on physical experiment. The study builds upon an earlier work-in-progress report (Cook et al. 2021). Two Remote IBLAs that have been adapted from their physical form, the Spool IBLA and the Rolling Cylinders IBLA (Self, Widmann and Adam 2016) are presented. The study of student uptake of the Remote IBLAs contains two parts. First, students are asked to compare their expected quality of learning of combined video and simulation to video alone and to simulation alone. Second, perceptions and performance of students using Remote IBLAs are compared to students using Physical IBLAs. To measure perception, students were asked to rate their learning and motivation in either the remote or physical mode. To measure performance, the correctness of student post-activity responses on targeted questions from the Dynamics Concept Inventory (DCI, Cornwell and Self 2020) are compared.

To pursue the efficacy of Remote IBLAs, we asked the following research questions:

1. How do students report that simulations alone, videos alone, or both simulation and video of IBLAs provide resources for them to learn difficult concepts in mechanics?
2. How do students' perceptions of learning and motivation and students' performance on end-of-course concept inventory questions compare between Remote IBLAs and Physical IBLAs?

Free access to the IBLAs, including simulations, handouts and instructions is available to instructors through the Concept Warehouse (Koretsky et al. 2014).

BACKGROUND

In this section, we first present the pedagogical foundations of the dynamics IBLAs. Then the affordances for virtual laboratory simulations upon which the remote IBLA simulation was constructed are described.

Conceptual Learning Through Cognitive Conflict

Cognitive conflict, one of the classic approaches to promote conceptual change (Prince et al. 2020), forms the pedagogical foundation for the dynamics IBLAs. Lee and Byun (2012) define cognitive conflict as "a perceptual state of the discrepancy between one's mental model and the external information recognized (internal-external conflict), or between different mental models of one's cognitive structure (internal conflict)" (p. 945). Challenging a student's naïve conceptions (and current cognitive structure) by presenting anomalous data or information is widely regarded as an important first step in promoting conceptual growth; however, cognitive conflict alone is not sufficient for cognitive change (Posner et al. 1982). The context in which this conflict is introduced also plays a major role in conceptual growth.

Limon (2001) recommends a number of strategies to create a productive cognitive conflict experience for students. The student must be motivated by and interested in the topic being covered, and the activity should activate the student's prior knowledge. In the case of engineering dynamics, students have typically encountered the mechanics principles involved during their physics courses and commonly can also relate the scenarios presented to their prior experiences in the world around them (e.g., a can rolling down a slope or pulling on a yo-yo string). Limon adds that students must have epistemological beliefs consistent with constructivist theories of learning, and must also possess adequate reasoning abilities to process the learning activity. Similarly, Chan et al. (1997) stress the importance of "knowledge-building activities" that require students to recognize inconsistencies and attempt to address them (Chan, Burtis, and Bereiter 1997). As Pintrich (1999) summarizes, "it is not useful for teachers to create tasks that increase the opportunities for cognitive conflict and then leave students entirely to their own devices to resolve the conflict" (cited in Limon 2001, p. 367).

Inquiry learning has several different definitions in the context of science and engineering instruction (Furtak et al. 2012). In this study, we follow the characteristics of inquiry identified by Minner, Levy, and Century (2009, p. 574):

"1. Learners are engaged by scientifically oriented questions.

2. Learners give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions.
3. Learners formulate explanations from evidence to address scientifically oriented questions.
4. Learners evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding.
5. Learners communicate and justify their proposed explanations."

Such framing aligns with the inquiry-based learning activities reported by Prince et al. (2016) in heat transfer and thermodynamics and our own work in dynamics. To this effect, the IBLAs developed in this study use the framework proposed by Laws, Sokoloff, and Thornton (1999), which includes:

1. A learning cycle beginning by having students make a prediction,
2. Having observations of the physical world provide authority, and
3. Emphasizing conceptual understanding.

Our use of computer simulations in the current study invokes a fourth principle,

4. Making appropriate use of technology.

Principle 4 is enabled by the affordances of the technology, as described next.

Affordances of Virtual Laboratories

The dynamics simulations developed for the remote IBLAs are a form of virtual laboratory (Koretsky and Magana 2019). One affordance of virtual laboratories is the ability to provide representations of phenomena unavailable in the physical laboratory (Koretsky and Magana 2019). Physical laboratories are inherently limited by what is observable in the natural world, whereas virtual laboratories can be designed to provide additional information to convey specific concepts. Therefore, some argue that virtual laboratories with complete fidelity to reality do not make full use of the medium, as such fidelity detracts from their capacity to provide pedagogical visualization and structuring of the desired phenomena (Lindgren and Schwartz 2009). For example, in chemistry and chemical engineering contexts, virtual laboratories have been developed to visualize molecular structures and thermodynamic processes invisible to students at the macroscopic level (Bowen, Reid and Koretsky 2014; Dorneich and Jones 2001; Schank and Kozma 2002). Similarly, molecular simulations have been developed to demonstrate emergent mechanical and electrical properties of materials from microscopic phenomena (Brophy, Magana and Strachan 2013; Corter et al. 2007; Sengupta and Wilensky 2009). Virtual laboratories that have been developed for mechanics typically are in the context of physics education, rather than engineering education (Van Joolingen and De Jong 2003; Wieman, Adams and Perkins 2008). Due to the differing focuses and learning outcomes between physics and engineering dynamics courses, we have developed simulations explicitly for undergraduate engineering students. These simulations have been designed to visualize critical force and velocity vectors: a key affordance over their physical counterparts.

Comparisons of the effectiveness of virtual laboratories relative to physical laboratories have been reported in the context of circuits (Kapici, Akcay, and De Jong 2019; Zacharia and De Jong 2014). Similar learning gains were demonstrated among students who conducted the physical laboratory alone and the virtual laboratory alone for simple circuit configurations, whereas gains were higher in the virtual laboratory for complex circuit configurations (Zacharia and De Jong 2014). This finding can be attributed to the ability of the virtual laboratory to provide additional representations. Other work has emphasized the utility of combining both delivery modes in sequence, where students achieved higher learning gains than using either modality alone (Kapici, Akcay, and De Jong 2019). The authors attribute this benefit to the novel affordances provided by both experiences which complement each other. Correspondingly, the remote IBLA designed for this study uses video recordings of the physical laboratory followed by web-based simulations for the virtual laboratory.

Vectors and free-body diagrams are critical representations for describing mechanical systems in engineering dynamics. Students need be fluent with these representations to productively engage in applied content, and often, students struggle with interpreting such information (Davishahl et al. 2019). For a dynamics virtual laboratory, it is desirable to visualize the force vectors applied to a body as this communicates important information regarding forces and moments. To avoid introducing too much complexity and detracting from the activity effectiveness, a Visible Thinking Framework (Cheong and Koh 2018) can be used for informing virtual laboratory design. This framework requires students to be familiar with the laboratory content such that they will not be overwhelmed by the content/design, and advocates for clear communication of “key cognitive processes in learning and problem-solving” (p. 58235) to the students by the instructor. The designer should clearly identify the components of a heavily visualized virtual laboratory on which students should focus their attention, and the activity must be designed to visualize the phenomena in a pedagogically effective manner.

Reviews of previous mechanics virtual laboratories have found that many simulations and animations were not designed attending to students’ cognitive load (Ha and Fang 2013). According to Cognitive-Load Theory (Sweller 1988), student working memory has limits and designers should design virtual laboratories than do not overload the students’ working memory (Andersen and Makransky 2021). Citing the psychological literature, Ha and Fang (2013) state that computer simulations are not even as helpful as still images for learning. Their position implies mechanics simulations would provide marginal benefits over a series of still pictures containing similar information. However, there are many ways a virtual laboratory can represent a phenomenon. We argue that by designing the virtual laboratory to provide critical but abstract vector representations, but also accounting for cognitive load, an interactive virtual laboratory can be developed to obtain conceptual learning gains similar to the analogous physical IBLA. We describe such a design next.

REMOTE IBLA ACTIVITY DESIGN

The Remote IBLA instruction design was directly based on preexisting worksheets developed using a "predict-observe-explain" sequence for physical activities. Prior work has shown that students have higher normalized gains on targeted DCI questions when using IBLAs, while still performing as well or better on common final exam traditional problems (Self and Widmann 2017). For each Remote IBLA described, a video recording of an instructor demonstrating the activity was provided. Students were then provided a link to a 2-D rigid body physics simulation that illustrated the same phenomena as the corresponding physical experiments.

Videos

Figure 1 shows screenshots of the two videos for the Remote IBLAs used in this study; links to the video files can be found in the figure captions. Figure 1a shows the Spool IBLA where students predict the direction a spool will accelerate/roll when pulled by a string in a specified direction (among other questions). The instructor subsequently pulls up on the Spool string after ensuring the body is completely at rest, and the spool moves leftwards. Through a series of cases, students explore the relationship between forces, moments, linear acceleration, and angular acceleration. Using these principles, students must predict the direction of rotation for a given case, the direction of the friction force, and how the magnitude of friction compares to the pull force on the string.

Figure 1b Shows the Rolling Cylinder IBLA where students predict which of two cylindrical objects will reach the bottom of the ramp first. In the video, the instructor uses a typical laboratory

a b

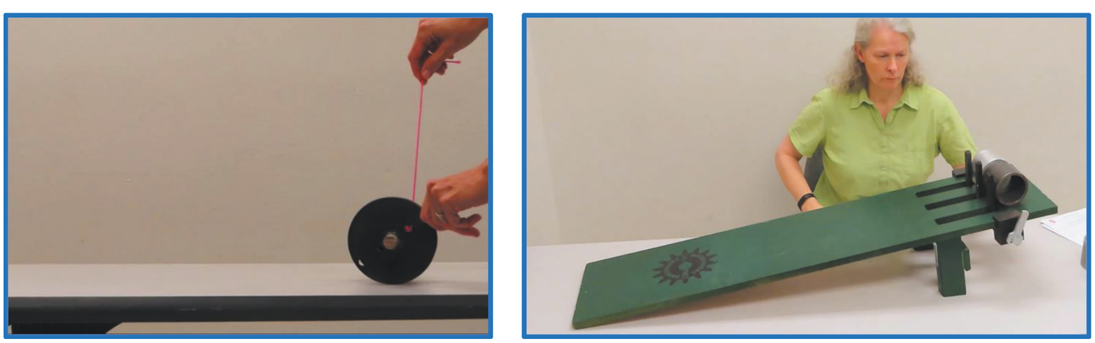

Figure 1. Screenshots of videos of Case 1 for the (a) Spool IBLA (video available at https://youtu.be/qZ3ph8YFr2A) and (b) Rolling Cylinders IBLA (video available at https://youtu.be/K5SXM2jF4Ow).

setup, which incorporates a lever to hold the cylinders at an equidistant point from the bottom of the ramp. Once the cylinders are placed side-by-side at the ramp apex, the instructor releases them, and viewers will observe which reaches the bottom faster. The Rolling Cylinder IBLA focuses on the role of mass distribution (i.e. rotational inertia) and the principle of work and energy on the velocity of objects. Through a series of cases, students must predict, between two provided cylinders, which will roll down the provided incline faster.

Simulations

The virtual laboratory simulations were previously developed to alleviate shortcomings inherent to in-person dynamics laboratories. Notable issues include releasing objects simultaneously, difficulties observing slight differences between objects/cases due to the fast speed, the ability to "see" friction force, and long experiment setup time. The simulation design includes several interface buttons, real-time graphing of sampled simulation parameters, and the visualization of force and velocity vectors.

Figure 2 shows a screenshot of the Spool IBLA simulation for the case that corresponds to the video shown in Figure 1a. Students are tasked with predicting the direction a spool will roll when

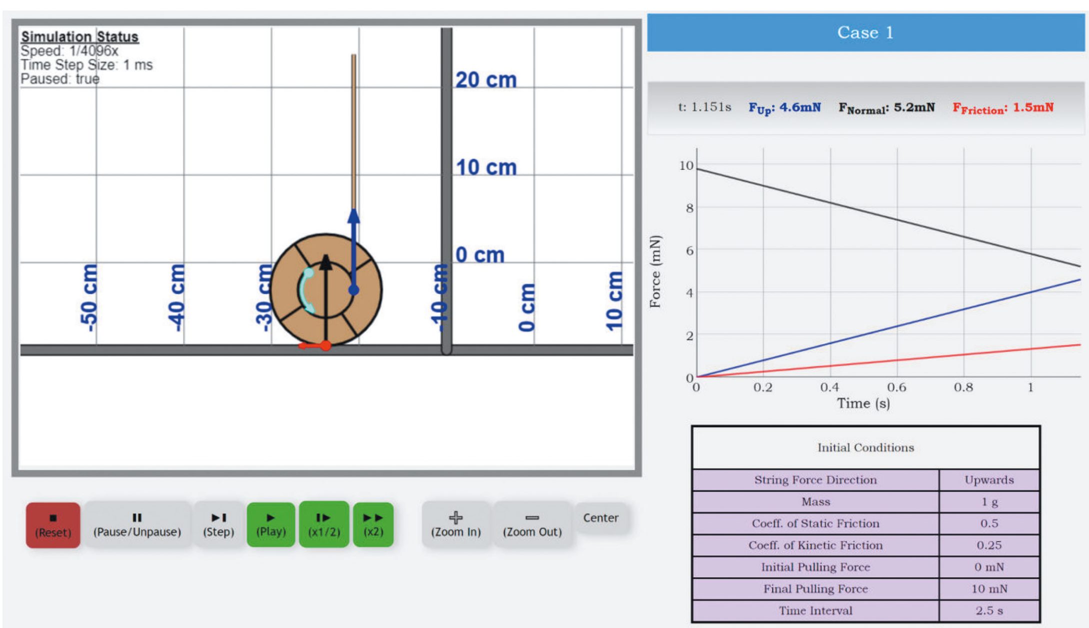

Figure 2. Screenshot of one case for the Spool IBLA Simulation. The simulation is available at https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/Spool1.html

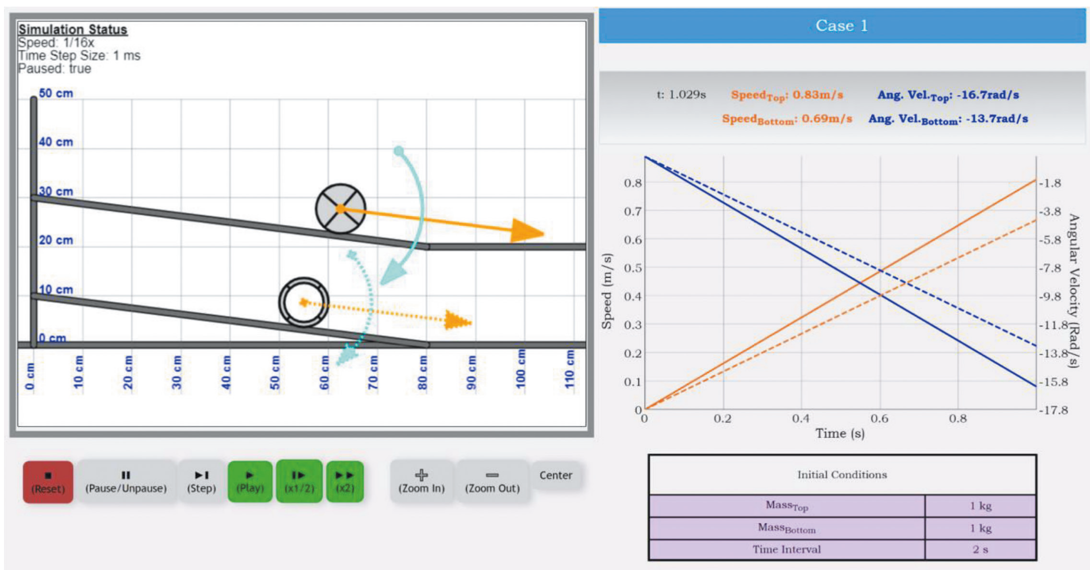

Figure 3. Screenshot of Case 1 for the Rolling Cylinders IBLA Simulation. The simulation is available at https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/RollingCylinder1.html

pulled by a string in a predefined direction. In Case 1, the string applies an upward linearly increasing force (blue vector) at half the spool's outer radius. The normal force of the spool (black vector) and the friction force (red vector) are displayed at the point of contact. The magnitudes of these three forces are plotted on the graph on the right. Angular velocity is denoted with a cyan arced vector. Pertinent initial conditions are summarized in the provided table. Likewise, Figure 3 shows a screenshot of the Rolling Cylinders IBLA corresponding to the video in Figure 1b. Students are tasked with predicting which of two cylindrical objects will reach the bottom of the ramp first. The angular velocity is denoted with a cyan arced vector, while the linear velocity is drawn with an orange vector whose origin is at the center of mass. Solid lines refer to the top object, while dotted lines refer to the bottom. Angular velocity is plotted with blue and speed is plotted with orange. Links to both of these simulations can be found in the figure captions.

The mechanics simulations were implemented assuming a 2D rigid body physics model. To implement the preexisting physics exercises in a computer simulation, a robust and accurate physics engine was selected based on several criteria. We required the simulation to be 100% Client-End (e.g., computed on a student/client device), accessible via web browser, and to provide robust (99%) accuracy relative to ideal cases over a time span less than ten seconds. To satisfy these requirements, we used a port of the C++ Chipmunk Physics engine in JavaScript. Chipmunk Physics was developed as a lightweight engine intended for mobile game development during the 2000s. It has since been open-sourced on GitHub and transcribed to JavaScript. The engine uses an iterative approach for computing jointed constraints between objects (i.e. pivots, pins, rope), and conserves system energy effectively over local time scales. Other engines were considered, including Box2D.js and Matter.js. However, these engines introduce non-idealities including energy loss in joints and translational drag, both of which are difficult to compensate for. An executable JavaScript copy of each simulation case is hosted on the Concept Warehouse for student instruction.

The inclusion of vector representations to visualize force and velocity concepts leverages a key affordance of virtual laboratories. With physical experiments or videos, these abstract representations must be presented independently of the experimental phenomena, if at all. For example, the Free-Body Diagrams (FBDs) that are used to represent the forces applied to an object might be presented as still images in a laboratory hand-out. The Spool simulation reported here shows animation of varying friction, normal, and tension forces across all time-instances of the simulation, allowing students to connect the abstract forces to the motion of an object. Similarly, the Rolling Cylinders simulations visualize translational and angular velocities at each instant in time, allowing students to compare the relative magnitudes across the two cylinders for each case.

However, representations of force or velocity add information, and simulation design needed to consider students' cognitive load as well. This consideration led to deliberate choices about which aspects were critical for learning and what aspects to omit. For example, we did not implement force vector visualization of gravity and made deliberate choices for displaying velocity or acceleration depending on the IBLA learning goals. Raw vector magnitudes and angles are omitted from the simulation window and were alternatively stored in a graph (when applicable). Our rationale is that, for understanding force/velocity concepts, it is more beneficial for students to see the *relative* magnitude and direction of these vectors in the window allowing students to see how friction is influenced by string tension and normal force magnitude in the Spools activity. For the Rolling Cylinders, it is more valuable to see the how the velocity vector changes over time, as this results from their different moments of inertia. A graph is provided as a tool to store, present, and compare simulation parameters for students seeking a quantitative summary of each simulation.

METHODS

Participants and Setting

In a naturalistic setting, students' perceptions and performance of the Remote IBLAs were collected. Then, a split design experiment was used to compare perceptions and performance of two cohorts of students with one cohort completing only the Remote IBLAs while the other cohort completing only Physical IBLAs. Both cohorts were comprised of second and third-year engineering students enrolled in engineering dynamics at the same large state university, but the data were collected in different years. While demographic data of the participants were not directly collected, the course studied is required for engineering majors and the representation is likely close to that reported from institutional data (28% women, 72% men; 15% Asian, 14% Hispanic or Latinx, 56% White, and 15% another category).

Perception data were collected through a Likert scale instrument, and total student response counts are summarized in Table 1. There were 150 student responses for the Spool IBLA and 143 responses for the Rolling Cylinders IBLA for the remote condition and 66 responses for the Spool IBLA and 64 responses for the Rolling Cylinder IBLAs for the physical condition. Incomplete submissions which did not contain information for both Learning and Motivation items were removed, which is reflected across the decreased Likert responses in the reported results. Performance data were collected using the Dynamics Concept Inventory (DCI). DCI data were collected the last week of the quarter, 2–3 weeks after the two activities were conducted. Response counts are also provided in Table 1. For the remote sessions, students could complete the DCI as part of several ways to obtain "participation points," resulting in 97 responses for the Spool-related question and 99 responses to the Rolling Cylinders-related question. The physical implementation gave an effort-based homework score for completing the DCI, resulting in 65 responses for the Spool and 66 responses for the Rolling Cylinders questions.

While students from the same course from the same institution were compared, instruction for the Remote IBLA condition was altered more generally due to the COVID-19 pandemic. Students could attend one of two synchronous remote 50-minute lecturers (Mon-Wed-Fri), or choose to watch recordings of the class. Additionally, students were required to sign up for a one-hour recitation session led by undergraduate Learning Assistants (Cao et al. 2018). These sessions focused on conceptual understanding, and three different IBLAs were used during the quarter, two of which

Table 1. Student response counts by delivery mode and activity for the IBLA and DCI surveys. Incomplete IBLA Likert surveys were removed in subsequent analyses.

Mode	Activity	IBLA Total Responses	DCI Total Responses
Remote	Spool	150	97
	Rolling Cylinders	143	99
Physical	Spool	66	65
	Rolling Cylinders	64	66

are reported here. Students worked in groups of 3-4 while the LAs visited different breakout rooms to ask probing questions and help guide the students. The class was divided into six sections of approximately 35 students per section.

For the Physical IBLA condition, the course was scheduled similarly as the Remote IBLA condition. The course met for three 50 minute in-person lectures. The IBLAs were completed during one of these 50-minute sessions. These sessions were led by the course instructor and did not use undergraduate Learning Assistants. Students were provided paper worksheets and answered identical questions to the electronic format of the Remote condition. Links to these worksheets are provided in Appendix A and Appendix B. In groups of 3–4, students used provided materials to engage in the dynamics cases described in the worksheets.

The in-person, Physical IBLA exercises used are identical to those previously reported (Self, Widmann and Adam 2016). The Remote IBLAs followed this same sequence as much as possible. For the Spool IBLA, students are given a physical scenario as shown in Appendix A, and asked to predict the direction of the acceleration and of the friction force. Appendix A shows the different scenarios for the Spool IBLA. For the Rolling Cylinders IBLA, students are presented different objects and asked which one will "win the race." The different scenarios for the Rolling Cylinders IBLA are shown in Appendix B. For the remote condition, students returned to the main Zoom room between cases, where the LAs guided students to use scientific reasoning to explain the relevant phenomena.

Data Sources and Analysis

For both the physical and remote conditions, all student data were taken directly from the Spool IBLA and Rolling Cylinders IBLA online quiz activities collected using either the institution's learning management system or the Concept Warehouse.

For student perceptions, Likert scale and free response survey items were used. In the remote condition students were given post activity survey questions after they completed the activity where they were asked to rate how much they agree with the following statements with a Likert scale:

- Seeing only the video (no simulation) would allow me to understand the phenomenon and would result in the same learning (e.g., I don't really need the simulation).
- Seeing only the simulation (no video) would allow me to understand the phenomenon and would result in the same learning (e.g., I don't really need the video.)
- Both the video and the simulation contributed to my understanding of the phenomenon and contributed to my learning (e.g., I prefer having both the video and the simulation).

Subsequently, students were provided a text box to explain their Likert scale selections and "differentiate between how the video and simulation helped their learning."

In both the remote and physical conditions, students were asked to rate how much they agree with the following statements with a Likert scale:

- This activity helped me learn about dynamics.
- This activity was interesting and motivating.

Student performance was measured via the DCI, a 29-question multiple choice assessment gauging student understanding and misconceptions about dynamics content (Cornwell and Self 2020). Questions that aligned to the content of each IBLA were identified and used as a measure of student learning.

Statistically significant differences in the Likert-scale perception data were determined from non-parametric statistics, using the Mann-Whitney U for the case of two groups (e.g., remote vs in-person) and the Kruskal-Wallis H for the case of three groups (e.g., video alone, simulation alone, both). Significant differences for the performance data were determined with parametric statistics using a z-test. A significance level of α=0.05 was used, and the Bonferroni correction was used in the case of multiple comparisons. For analysis of the free-response quotations, the object of each statement fragment was first identified (video, simulation) and then common themes were extracted from the quotes that illustrated student perceptions of how that mode supported learning. Student comments were generally consistent with the quantitative Likert data, and representative quotations were selected based on common themes.

RESULTS

Perceptions of Video, Simulation, and Both

Likert scale results for different media (video alone, simulation alone, video and simulation) and IBLA activities (spool, rolling cylinders) are shown in Table 2. For each activity, Video and simulation together was viewed by students as contributing more positively to their understanding of the phenomenon and learning than either video alone or simulation alone. A Kruskal-Wallis non-parametric test

Table 2. Likert scale response (1=strongly disagree) to (5=strongly agree) to the contribution of the medium to understanding the phenomenon and learning.

Medium	Activity	1	2	3	4	5	n	Activity Average	Grand Average
Video Alone	Spool	15	68	25	30	9	147	2.7	3.0
	Rolling Cylinders	3	38	24	47	23	135	3.4	
Simulation Alone	Spool	16	56	29	37	9	147	2.8	2.7
	Rolling Cylinders	22	60	19	28	6	135	2.5	
Video and Simulation	Spool	1	3	21	65	57	147	4.2	4.1
	Rolling Cylinders	0	7	29	56	43	135	4.0	

revealed that there was a statistically significant difference between medium ($H = 215.6$, $p < 0.0001$) but no significant difference between activity ($H = 1.1$. $p = 0.29$). A post hoc pairwise comparison using Bonferroni correction showed that all pairwise medium differences were significant.

Following statistical analysis, we examined the free-response survey questions to understand why students viewed video and simulation together as preferable to video only or simulation only. Generally, students felt each mode served a different purpose, as indicated by the following student:

> *"To me, both the video and the simulation were individually sufficient in helping me understand this concept. However, having both is useful because the video shows this concept in real life, while the simulation gives more information."*

Students found the video readily helps them understand "what" happens in each case. The simulation however provides "more information" such as forces, velocities, and other phenomena. Another student summarizes this concisely:

> *"The video showed "what" and the simulation showed "why/how" the phenomena happened."*

Students believe the simulation communicates more information to them, which can be valuable for developing conceptual understanding of the phenomenon in question as illustrated in the following quote:

> *"The video served as a kind of reality check because it actually shows the real life demonstration of the phenomenon and how it may prove a student's initial instincts wrong. There quite a bit more cognitive dissonance when we are told to formulate a hypothesis and discuss it to the point of understanding/agreement with our groups then are shown that we are flat out wrong. Computer simulations are helpful for seeing more of the "why" rather than the "what," meaning we can more easily understand after watching the video of our professor actually conducting the experiment and seeing the results so we can observe the arrows and magnitudes of the different energies."*

Remote vs. Physical IBLAs

Perceptions of learning and motivation

Table 3 shows Likert scale results for the learning and motivation items. A Mann-Whitney non-parametric test revealed that there was not a statistically significant difference between

Table 3. Likert scale response (1=strongly disagree) to (5=strongly agree) to the learning and motivation items.

	Mode	Activity	1	2	3	4	5	n	Activity Average	Grand Average
Learning	Remote	Spool	4	6	11	98	25	144	3.9	4.1
		Rolling Cylinders	0	2	8	77	47	134	4.3	
	Physical	Spool	0	0	4	46	15	65	4.2	4.1
		Rolling Cylinders	1	1	5	39	17	63	4.1	
Motivation	Remote	Spool	3	17	30	84	12	146	3.6	3.8
		Rolling Cylinders	0	5	23	77	29	134	4.0	
	Physical	Spool	0	0	11	45	9	65	4.0	4.0
		Rolling Cylinders	1	1	9	35	17	63	4.0	

perceptions of learning in physical and remote delivery (U = 0.06, p = 0.81). However, there was a significant difference in activity, with students perceiving they learned more in the Rolling Cylinders IBLA (U = 9.02, p <0.01). There was a statistically significant difference in student motivation by instructional mode (U = 6.81, p < 0.01) as well as by activity (U = 13.4, p < 0.001) with students more motivated by the physical mode and by the Rolling Cylinders IBLA activity. A post-hoc analysis showed no difference in motivation between remote and physical modes for the Rolling Cylinder IBLA (U = 0.75, p < 0.39), but a significant difference in the Spool IBLA (U = 8.5, p < 0.01) with students more motivated by the physical IBLA.

Measures of learning

Student performance on two Dynamics Concept Inventory (DCI) questions is summarized in Table 4. For each question, a two-proportion z-test indicates no statistically significant differences in student performance between the two modes for either the question associated with Rolling Cylinders (p = 0.23) or the question associated with Spools (p = 0.054). Consistent with their perceptions, students scored higher on the Rolling Cylinders question, but the relative scores do not account for possible differences in question difficulty.

Table 4. Student performance data for Dynamics Concept Inventories (DCI).

Mode	Question Content	Total Correct	Total Incorrect	n	% Correct	% Correct (Both Activities)
Remote	Spools	59	38	97	61%	76%
	Rolling Cylinders	90	9	99	91%	
Physical	Spools	49	16	65	75%	80%
	Rolling Cylinders	56	10	66	85%	

DISCUSSION

IBLAs provide an evidence-based pedagogy to help students build conceptual understanding by having them reconcile discrepant events (Laws, Sokoloff, and Thornton 1999; Posner et al. 1982; Prince et al. 2020). In this study, we developed two Remote IBLAs based on successful corresponding hands-on physical IBLAs and performed a preliminary study of student perception and performance. The design of the Remote IBLAs was based on two principles: providing abstract vector and graphical representations (Davishahl et al. 2019) not available in physical laboratories while simultaneously attending to students' cognitive load (Ha and Fang 2013; Sweller 1988). To this end, the Remote IBLAs contained two elements, a video demonstration of the classroom experiment and a virtual laboratory that included a simulation with added vector and graphical representations.

The first research question focused on student perceptions of the importance of video and simulation elements in the Remote IBLAs to their learning. For reasons of instructional integrity, we did not test each of the two Remote IBLA elements alone. Rather, we asked students their perceptions of video alone, simulation alone, or video and simulation together after they had experienced both. Per the Likert survey results in Table 2, students clearly prefer having both video and simulation formats available to help them learn. The rationale for this preference was indicated in the student free responses. Students articulated each format had unique merits. They stated the video provides the "what" - a concrete example of the phenomenon under investigation that concretizes the experimental outcome. Additionally, video primes the students for the simulation subsequently made available. The simulation provided information "why" the phenomenon occurs - with the added abstract vector representations (i.e., force and velocity vectors) giving students the opportunity to develop their mental models of the physics underlying the observed phenomena. Students stated concerns that if the simulations were used without video, the IBLA would be too abstract, especially if the student is overwhelmed by the correspondingly higher cognitive load. Some students indicated the simulation alone has the potential for being perceived as less real.

The second research question compared perceptions and performance of delivery mode (remote or physical). There was no significant difference in mode in student perceptions of IBLA effectiveness on their learning (Table 3), a perception consistent with their end-of-term performance on concept inventory questions (Table 4). Abstract disciplinary representations, such as force and velocity vectors, require significant practice for students to gain fluency. For second-year students, vector literacy gained from prior statics and physics coursework was leveraged in integrating these representations within the simulations to potentially improve the learning experience of students.

The student perceptions of motivation were more complex, with students reporting they were less motivated in the remote mode for the Spool IBLA compared to the physical counterpart. However, there was no difference in the Rolling Cylinders IBLA. Such differences could be due to the different characteristics of each task or due to the time in the term the task was delivered. Some motivational differences may be attributed to more general student frustrations amid the COVID-19 pandemic, such as the less engaging experience yielded by instantaneous shifts to remote university courses (Koretsky 2022). On the other hand, researchers have argued that there is an inherently motivating aspect when students work with their hands performing real physical experiments (de Jong, Linn, and Zacharia 2013; Rau 2020). In future studies, this confounding effect could be investigated by a split design experiment where students either complete the remote or physical IBLAs when courses return to in-person administration.

While this study was conducted in the context of two experiments in dynamics (Spool and Rolling Cylinder), these preliminary findings can be considered for developing remote learning tools in other contexts. Judging by student performance and perspectives of their performance, Remote IBLAs could provide a plausible alternative to Physical IBLAs, requiring less resources to implement, while producing similar learning. Technology design should incorporate both video, which can concretize the phenomenon - making it real - and simulation, which can integrate abstract representations for students to process as they are engaged in the activity. Simulations also allow interactions not possible in real experiments such as pausing, slowing, resetting etc. Importantly, designers should gauge the typical cognitive load on students. A possible reason that students prefer having both a simulation and video is that each provides cognitive tradeoffs for the student experience. The video used in this study provides a lower cognitive load on the student and prepares them for viewing the corresponding simulation. The simulation, conversely, places a higher cognitive load on the student and provides them additional information via vector and graphical representations to conceptualize the phenomena at hand. Conversely, one could imagine a more complex experiment which would require a high cognitive load for students to process in a video. In such a case, a simplified simulation could be developed to provide students a lower cognitive load point of entry. Thus, the scaffolding would be similar to that reported here but in reverse order. Finally, instructors using remote learning tools should be cognizant of engagement and develop strategies to address student motivation. Future research could clarify which characteristics of the simulations and physical scenarios improve student learning and engagement – for instance, how much do students interact with the simulations by rewinding, changing playback speeds, and stepping through the graphical results?

This preliminary study has several limitations and the results should be considered with those limitations in mind. The study was conducted in one course context at one institution and for only one cohort in each condition. The varying affordances provided by each delivery mode should be further tested with larger sample sizes of different student cohorts across several institutions and with different content. The Remote IBLA condition was delivered during the COVID-19 pandemic, which necessitated different classroom conditions than the comparative Physical IBLAs. Other differences in instruction included facilitation of the groups with the primary instructor leading the Physical IBLAs while undergraduate LAs led the Remote IBLAs. Only single measures of performance and motivation were used, and more robust instruments for conceptual understanding and motivation would add validity. However, despite these limitations, this preliminary study indicates that when video and simulation are combined, Remote IBLAs show promise to provide a broadly accessible medium to help students learn challenging concepts in engineering.

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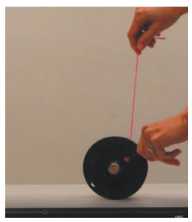
APPENDIX A – SPOOL IBLA

Link to worksheets for all cases:

https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-wksht/Spool_IBLA.pdf

Case 1 – Pull upward

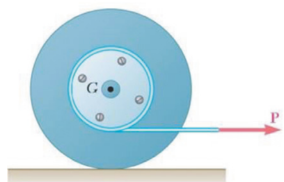


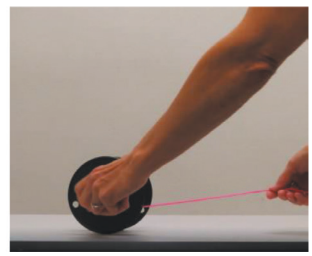
Video link: https://youtu.be/qZ3ph8YFr2A

Simulation link:

https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/Spool1.html

Case 2 – Pull right



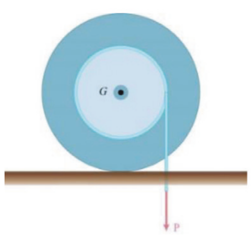


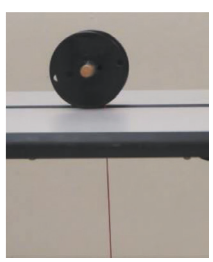
Video link: https://youtu.be/T_J0old5MLE

Simulation link:

https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/Spool2.html

Case 3 – Pull down





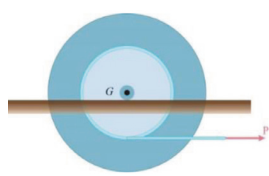
Video link: https://youtu.be/tRIIRQMLeoU

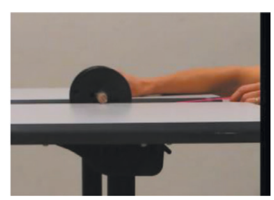
Simulation link:

https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/Spool3.html

Case 4 – Pull right

(rolls on smaller diameter hub)





Video link: https://youtu.be/2lkITMe-Tjk

Simulation link:

https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/Spool4.html

APPENDIX B – Rolling Cylinder IBLA

Link to worksheets for all cases:

https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-wksht/Rolling_Cylinder_IBLA.pdf

Case 1 – Cylinder vs Pipe

Video link: https://youtu.be/K5SXM2jF4Ow

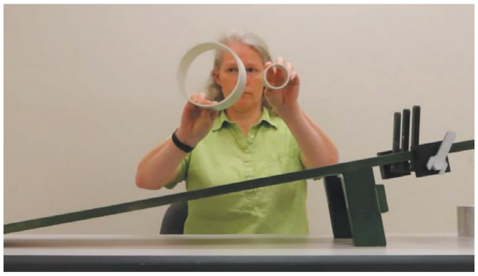
Simulation link: https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/RollingCylinder1.html

Case 2 – Large vs small metal cylinder

Video link: https://youtu.be/BTtZkla4aGk

Simulation link: https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/RollingCylinder2.html

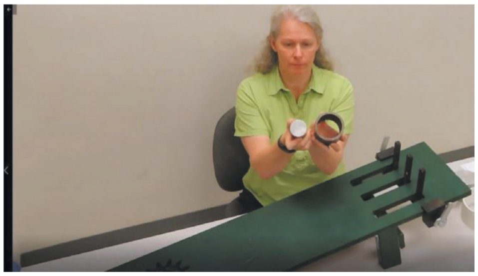
Case 3 – Large vs small PVC pipe



Video link: https://youtu.be/QN4KbbAucB8

Simulation link: https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/RollingCylinder3.html

Case 4 – Small cylinder vs large pipe



Video link: https://youtu.be/J8wUfAL1hnY

Simulation link: https://newjimi.cce.oregonstate.edu/concept_warehouse/test/ME-sims/RollingCylinder4.html