

Student engagement with statistical noise features in PhET's Projectile Data Lab simulation

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Many introductory physics lab courses intend to have students learn about concepts and practices of measurement uncertainty. However, studies have shown that learning goals around this topic are often not met. To improve students' proficiency with concepts and practices of measurement uncertainty, we developed a new, noise-enhanced PhET simulation, Projectile Data Lab, featuring statistical noise and measurement tools in the context of projectile motion. To validate the simulation design and provide insight into its effectiveness, we conducted 12 think-aloud interviews where students worked through an associated lab activity with the simulation. Through emergent coding of the interview transcript and screen recording, we found that students are successfully engaging with the ideas around measurement uncertainty associated with the simulation features. These findings suggest that the simulation and accompanying lab activity have the potential to enhance students' conceptual understanding of measurement uncertainty in an introductory physics lab setting.

I. INTRODUCTION

Many introductory physics lab courses acknowledge the importance of measurement uncertainty, as learning concepts and practices of measurement uncertainty often form the main learning goals for these courses [1, 2]. However, studies by physics education researchers have shown that the learning goals around this topic are often not met, and that students often lack deep conceptual understanding of measurement uncertainty [3–6]. To improve students’ proficiency with concepts and practices of measurement uncertainty, we developed a new PhET simulation, *Projectile Data Lab* (PDL), featuring statistical noise and measurement tools in the context of projectile motion, as well as associated lab activities.

PhET simulations (sims) are well-established learning tools that create inviting, intuitive, exploratory environments allowing for rapid iteration with a focus on conceptual development through implicit scaffolding [7–12]. The sims’ research-based design has been shown to promote student agency in many aspects of scientific practices, such as asking questions, conducting experiments, identifying causal relationships, and reflecting on results [11, 13, 14]. With the design and publication of PDL [15], we aim to bring these benefits to help students learn core ideas around measurement uncertainty, so they are better prepared to perform experiments in their introductory lab courses.

In this paper, we present research on student engagement with the ideas around measurement uncertainty and statistical noise features in the PDL sim. With this first study, we aim to validate the sim design and provide insight into its effectiveness. Here, we address the following two research questions:

- RQ1: In what ways are students engaging with the PDL sim and its built-in statistical noise features, in the absence of any external guidance?
- RQ2: How does engaging with the PDL sim impact how students estimate the size of random uncertainty of a single measurement with scaffolded guidance?

It is important to emphasize here that we are not advocating for removing hands-on activities from lab courses. We are, however, proposing to help students learn core experimental practices using this new PhET sim before they enter the lab. This would allow students to engage more productively with hands-on activities, applying and deepening their understanding of measurement uncertainty, rather than struggling to learn these concepts for the first time during limited lab time.

II. METHOD AND DESIGN

A. Design of the simulation and lab activity

To guide the development of the PDL sim and its accompanying lab activities, we began by identifying clear learning goals. Prior research on the Survey of Physics Reasoning on Uncertainty Concepts in Experiments (SPRUCES), a lab-based instrument designed to measure student understanding of measurement uncertainty, had identified assessment objectives, validated as both important to instructors and challenging for students through interviews [2, 6]. These assessment



FIG. 1. The Variability screen of the PDL sim. Students can choose from six different launchers with varying amounts of statistical noise in their launch speed and angle, as well as three different projectile types with varying sizes. The variation in the projectiles’ horizontal ranges can be visualized in the histogram panel.

objectives [6] informed and motivated the learning goals for the new sim and lab activities.

To help students achieve these objectives, we designed specific features into the PDL sim, including adding different levels of statistical noise to the launch speed and angle for each launcher, which results in variation in the projectiles’ trajectories and horizontal ranges. Students can select which launcher to investigate, adjust its orientation, choose the projectile type, and collect data. A histogram panel displays the distribution of horizontal distances for the projectiles that have landed. These design features are seen in Figure 1.

For this study, we focus on the learning goal of “estimating the size of random/statistical uncertainty by considering instrument precision.” A few design features were explicitly included in PDL to help address this learning goal. First, different projectile types have varying sizes (roughly 2 m for the piano and pumpkin, and 0.5 m for the cannonball), and both the pumpkin and the piano smash upon landing, creating a source of uncertainty. In addition, to mimic the real-world lab setting, the sim does not display the exact value of the horizontal distance the projectile traveled. Instead, students need to either use the white markings on the field or the digital measuring tape tool to determine the horizontal distance. The markings on the field have a uniform spacing that is defined by the bin width in the histogram panel, and thus can be treated as an analog ruler that measures the horizontal distance of the projectiles, as shown in Figure 2 (a). The digital measuring tape tool requires students to position the end of the measuring tape “by hand” and displays only the measured distance to a precision of 0.1 m, as shown in Figure 2 (b).

PhET sims are not intended to be used in isolation. To support and examine student achievement of the learning goals, we also developed associated lab activities that pair with PDL. These activities are designed for students in introductory lab courses to work through (e.g., as an assigned prelab activity) to learn core ideas around measurement uncertainty. In line with the well-established practices for using PhET sims, we start the lab activities with open exploration of the sim, and scaffold the rest of the activities using the “contrasting cases” approach [16, 17], where students are asked

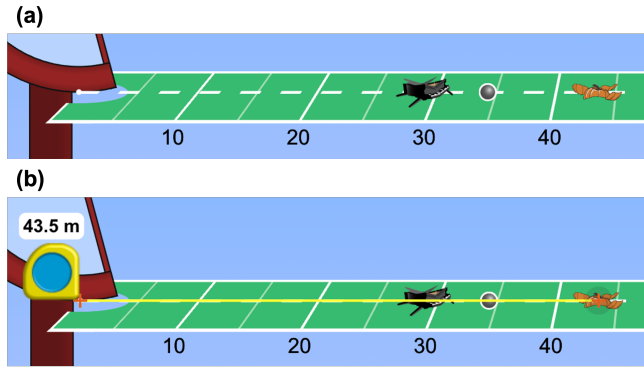


FIG. 2. An example setup for measuring horizontal distances of single projectiles using (a) markings on the field and (b) measuring tape tool in the PDL sim. The three single projectiles (piano, cannon ball, and pumpkin) have varying sizes that contribute to the measurement uncertainty of the horizontal distances.

to evaluate measurement uncertainties in different scenarios. For the first one, the activity can be divided into two parts. In the first part, the students were asked to “take about 5 minutes to explore the sim” without any explicit guidance, and then “write down 2 observations in the lab notebook related to the launcher or the projectile.” In the second part, the students were asked to “choose a launcher and a launch orientation, then launch a single cannonball, a single pumpkin, and a single piano.” Afterwards, for these three single projectiles, the students were asked to first “set the bin width to 5 m, so that the markings on the field are 5 m apart,” and then “estimate the horizontal distances that each of the projectiles has traveled using the markings on the field.” Finally, the students were asked to “measure the horizontal distances of these projectiles using the measuring tape tool.” We pilot tested these activities through student interviews to ensure that the activities were appropriately interpreted by students.

B. Interview procedure and analysis method

To examine student engagement with the PDL sim, we conducted 12 think-aloud interviews, where students were asked to interact with the sim and work through the associated lab activity while explaining their reasoning aloud [18]. The students were recruited during the Spring 2024 and Fall 2024 semesters from calculus-based and algebra-based introductory physics courses at two large R1 universities. Out of these 12 students, 10 students are engineering majors, and 2 are life science majors; 8 are first-year students, 2 are third-year, and 2 are fourth-year. For the think-aloud interviews, the students were provided with the publicly available link to the PDL sim [15], as well as the lab activity in the form of a Google Doc that the students were asked to treat as a lab notebook. All interviews were conducted through Zoom with audio and screen recording, and lasted about 1 hour.

After transcribing the recorded interviews and collecting the students’ lab notebooks, we conducted emergent coding of all written, audio, and visual data to identify the common themes in terms of student engagement with the statistical

noise features in the PDL sim [19]. To address RQ1, we first analyzed the interview transcripts and screen recordings, in combination with the observations that the students wrote in their lab notebooks, to examine the sim features that the students actively interacted with during the open exploration process. To address RQ2, we analyzed what students reported for the horizontal distance measurements and the associated uncertainty in their lab notebooks, and examined their reasoning for reporting the uncertainties for these measurements in the interview transcripts to identify the sim features that the students incorporated when they were reporting their measurement uncertainties.

To ensure robustness of our results, we conducted a confirmatory inter-rater reliability study where a second researcher independently coded a subset of the data (10% of the total coded segments) [20]. The two raters resulted in a 90% agreement on all codes, which suggests that the raters agree on the codes and themes identified in this study.

The primary limitation of this study is that the sample consisted predominantly of first-year engineering students at R1 universities. As a result, the findings should not be generalized to a broader population without additional data.

III. RESULTS

A. RQ1: Student engagement with the sim during open exploration

During the 5-minute open exploration part of the activity, students interacted with the PDL sim on their own without explicit guidance, and then recorded observations that they found interesting in their lab notebooks. From the interview transcripts, screen recordings, and students’ lab notebooks for this part of the lab activity, we identified eight sim features the students explored, which we categorized into two main themes (see Table I).

The first theme centered on the measuring tools and functionalities that enabled students to collect and analyze data in an authentic manner. The sim included four key features: measuring tape tool, stopwatch tool, field, and histogram panel. Among these features, the histogram panel was the most explored during the think-aloud interviews, with seven out of twelve students actively engaging with its various functions. Of these, four students specifically noted the histogram plot, connecting the distribution to the variation in the projectiles’ horizontal distances. For example, one student commented:

“It looks like they’re landing in different spots each time I fire it. And there’s a little thing on top showing where they’ve landed [the histogram panel]... So it’s like making little distributions.”

Using the histogram plot, this student was able to relate the variation in the projectiles’ landing positions to a key idea associated with random uncertainties for multiple measurements, that repeated measurements will give a distribution of results not a single number.

TABLE I. Summary of key themes and categories identified for RQ1, and associated number of students who mentioned each.

Themes and Categories	Number of Students (out of 12)
Measuring Tools	9
Measuring Tape	4
Stopwatch	3
Field	5
Histogram	7
Statistical Noise	9
Launch Speed	6
Launch Angle	3
Launch Path	3
Horizontal Distance	6

The other three out of the seven students took note of the bin width feature, and related the histogram bin width to the spacing between the markings on the field. For example, one student commented:

“It looks like the bin width measures how wide, or how small, like the length is at the bottom [the field]. If I do 1 meter, you can see it’s labeled a little smaller than when I do like 5.”

This student was able to relate the bin width feature to the the markings on the field without any explicit guidance, which is a key prerequisite to associating it with the concept of instrument precision, a central idea associated with random uncertainties for a single measurement.

The second theme highlights the inclusion of statistical noise in the sim’s launch parameters and associated outcomes. These variations include launch speed, launch angle, launch path, and horizontal distance. Among these, six of twelve students mentioned the variation in horizontal distance, commenting that projectiles launched from the same launcher landed at different horizontal distances. For instance, when launching multiple cannonballs, one student commented:

“Normally with like these PhET programs, it would always be like within a very set variability. I’ve never seen something where I just got like one super far off like that, so that was interesting to see. Because normally I see that like if I was actually performing the lab, not if simulation was doing it.”

This student, in particular, articulated how the variations in the projectiles’ horizontal distances stood out to them, especially in the context of a computer sim, and compared such variations to their experiences with hands-on labs.

Another common observation was the variation in launch speed, also mentioned by six of twelve students. These students recognized that the launchers exhibited differences in how fast they launched projectiles. One student wrote in their lab notebook:

“It seems the launchers vary in power, or launch speed.”

This observation was echoed by the other five students, who described the variation in launch speed using related physical quantities such as force and power.

In contrast to the launch speed, only three out of twelve students commented on variations in the launch angle across different launchers. When launching multiple cannonballs, one student commented:

“The canon moves, so it looks like that’s where the variability comes from. I’d say that’s what causes like the error.”

This student not only noted the variation in launch angle, but also was able to identify the physical mechanism that is the source of this variation, and made this causal relationship.

B. RQ2: Student reasoning with random uncertainty of a single measurement during guided inquiry

For the guided inquiry part of the lab activity, the students measured the horizontal distances of three projectiles with finite sizes using both the markings on the field that are spaced 5 m apart and the digital measuring tape tool that measures distances with the precision of 0.1 m. The two main factors that influence the measurement and uncertainty for a single projectile are instrument precision and the projectile size.

While both projectile size and instrument precision play a role in the horizontal distance measurements, their relative impacts vary across the 6 contrasting cases (3 projectiles $\times$ 2 measurement approaches) scaffolded in the lab activity. When measuring the horizontal distances using the markings on the field, the instrument precision is the dominant source of uncertainty for the cannonball, while the instrument precision and projectile size contribute about equally to the uncertainty for the pumpkin and the piano. When measuring the horizontal distances using the digital measuring tape tool, however, the measurement instrument has sufficient precision to distinguish the size of the projectile, leaving the projectile size the dominant source of uncertainty.

From the interview transcripts and students’ lab notebooks for this part of the lab activity, we found that all 12 students recognized that these two factors impacted their measurements. While all 12 students recognized that the projectiles have finite sizes, only eight out of the 12 students factored the projectile size into their uncertainties. When asked why they reported a larger uncertainty of 4 m when measuring the horizontal distance of a pumpkin as compared to an uncertainty of 2.5 m when measuring that of a cannonball using the markings on the field, one student explained:

“I guess, the pumpkin’s hard because it broke, so it’s spread out. So it’s harder to really say exactly where it landed. So I might give that a bigger error, just because it’s more spread out the pieces of it.”

Moreover, there is additional nuance in the horizontal distance measurements, specifically related to the relative impact of the projectile size and instrument precision depending on the type of projectile. This nuance was recognized by 3 out of the 8 students who factored both instrument precision and projectile size into their uncertainties. When using the markings on the field, one student reported 1 m as the uncertainties for all three horizontal distance measurements, and explained:

“So my uncertainty, if I’m just going based on the field, is probably maybe roughly plus or minus 2.5, or maybe a little bit less. This cannonball is much, much closer to 50-meter mark than the 55-meter mark, so I think saying plus or minus 5 meters is a pretty broad uncertainty. Plus or minus 1 meter seems kind of reasonable. And in this case, I’m just assuming that the uncertainty would be based on that. Just the visual error in looking at it. Because I’m assuming that’s accurate. I think that reporting plus or minus 5 meters would be technically correct based on like my histogram and my bin width, but I also don’t think that’s what the question is asking someone to report as plus or minus 5.”

This student relied on the visual representation in the sim to justify their report of measurement uncertainties, while actively confronting their conceptual difficulty that a certain type of measurement instrument always has a specific uncertainty, which was shown to be common among introductory physics students [6].

When using the digital measuring tape tool, this student reported 0.5 m as the uncertainty for the cannonball’s horizontal distance, 1.5 m as the uncertainty for the pumpkin’s horizontal distance, and 2 m as the uncertainty for the piano’s horizontal distance. When asked why they now reported a larger uncertainty for the pumpkin than the cannonball, they explained:

“I guess the thing for the pumpkin is, you know, I can measure the distance to a certain part of the pumpkin, but the pumpkin is still spread out on the field. So I can’t really say exactly that. I wouldn’t. I don’t know if I’d say that the uncertainty is still 0.01[sic], because I still have some there’s some uncertainty in where I should measure... I think the uncertainty here just comes from the actual size of the object.”

Once again, this student overcame their conceptual difficulty that a certain type of measurement instrument always has a specific uncertainty through the sim visuals, and correctly identified that the projectile size is the predominant source of uncertainty.

The four students who did not factor projectile size into their uncertainty still recognized that projectile size impacted their measurements. One student reported the same uncertainties for all the projectile types when using the same measurement instrument (2.5 m for the markings on the field, and

0.05 m for the digital measuring tape tool), but they included this comment in their lab notebook:

“The projectile types and the breakage of projectiles that occurred may have had an influence on the scenario, as it was difficult to find the center of the pumpkin and piano, as they broke upon impact.”

While this student recognized that projectile size impacted their measurements, this idea did not translate to a difference in the reported measurement uncertainties. This student is likely exhibiting a common conceptual difficulty, specifically the idea that a certain type of measurement instrument always has a specific uncertainty and is not influenced by other contextual factors [6].

IV. CONCLUSIONS AND FUTURE WORK

In conclusion, we found that, during a 5-minute open exploration, most students readily discovered and engaged with the specific sim features that we designed to address the learning goals. Additionally, the students were able to connect sim functionalities productively with ideas related to random uncertainties for both a single measurement (instrument precision) and multiple measurements (repeated measurements will give a distribution), and recognize the inclusion of statistical noise in the sim without explicit guidance. These results support the validity of our feature design.

We also found that through the method of “contrasting cases” and appropriate scaffolding, all students were able to identify the multiple sources of uncertainty associated with their measurements, and most students factored these sources into their reported uncertainties. We observed a few instances where the sim visuals helped students actively confront a common conceptual difficulty associated with measurement uncertainty, that a certain measurement instrument has a set, defined uncertainty attached to it. This showcases that the sim and lab activity have the potential to improve students’ conceptual understanding of measurement uncertainty when used in an introductory physics lab setting. Instructors could assign PDL as a pre-lab activity to free class time for deeper data-analysis tasks.

While this study focuses on one specific learning goal of the sim, we created sim features and lab activities to address additional measurement uncertainty learning goals. Future work includes conducting and analyzing additional student think-aloud interviews to determine how working with interactive sims can broadly impact students’ conceptual understanding of measurement uncertainty, and then assessing how students transfer this understanding to real lab settings.

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