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Exploring Freshmen's Insight on Physics Measurement Uncertainty: Voices from the General Physics Course

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Abstract
Since secondary school, students have always learned measurement accuracy. Understanding measurement uncertainty is crucial, as is acquiring, handling, and analyzing measurement data. This study investigates first-year students' knowledge of measurement uncertainty in physics. This study utilized a one-group pre- and post-test design within a teacher research or self-study framework. This study involved 25 participants from an educational program at a university in East Java, Indonesia. The focus in this study was on four categories: (a) "repeated distance" (RD), (b) "using repeats" (UR), (c) "same mean different spread" (SMDS), and (d) "different mean same spread" (DMSS), based on Pollard et al.'s new codebook for the Physics Measurement Questionnaire. We observed moderate normalized gain in most of the four criteria following the lecture intervention. We also conducted a paired t-test and found statistical differences before and after the intervention. These results show freshmen struggle with understanding uncertainty in physics measurement based on their secondary schools' experiences, highlighting the need for a learning intervention combining theory and laboratory practice. These findings underscore the importance of enhancing education for future science teachers in secondary schools.

1. INTRODUCTION

Measurement and its uncertainty is one of the most important aspects of physics (Vignal et al., 2023; Wan, 2023). Physics in general is an experimental science (Holmes & Wieman, 2018). Traditionally, the first year of higher education in science will generally target learning outcomes for first-year students to master some basic principles such as measurement and measurement uncertainty (Allie et al., 2003; Holmes & Wieman, 2018). Laboratory experiences also require measurement skills so that students can explore and interact with concepts and practices in both physics and STEM in general (Pollard, Hobbs, et al., 2020; Smith & Holmes, 2021). According to recent studies, first-year students frequently struggle to understand scientific techniques and basic laboratory skills, which hinders their ability to study and think critically (Mandavgade et al., 2012; Wan, 2023). In addition, starting in secondary school, students are taught about measurement and measurement uncertainty, with the expectation that they will have the basic science skills needed for higher education.

One of the biggest challenges in measurement is that students tend to ignore measurement uncertainty and error analysis (Aubin et al., 2024; Dounas-Frazer & Lewandowski, 2018). On the other hand, many recent research results show that the ability in basic physics introductory laboratory is still not comprehensive in mastering laboratory concepts and skills (Carter, 2021). Students have a narrow knowledge of the scientific method and minimal laboratory experience at school, which is key for laboratory-engaged learning (El Masri et al., 2021; Kuang et al., 2020). This has led to a transformation of the learning process for first-year students, emphasizing the development of experimentation skills, thinking skills, and attitudes (Holmes & Wieman, 2018; Walsh et al., 2019; Wilcox & Lewandowski, 2017). Despite this shift of focus, there is still a gap in the research for how such competencies can be developed most appropriately, especially for the fields of measurement uncertainty and error analysis. While these are foundational competencies in physics, they are actually foundational in support of all scientific study. No explicit pedagogical conceptual frameworks and interventions have been provided to systematically address persistent shortcomings in these definitions and their practice by students.

The learning process at the higher education level is inseparable from the previous education process, although the college entrance examination questions tend to be significantly less in line with the curriculum standards in physics (Han & Xiang, 2024). In general, the transformation of learning at the global level in the introductory physics laboratory is to provide space for students to be actively involved in the authentic inquiry process (Werth, West, et al., 2023). The transformation process that occurs at the global level also needs attention from higher education educators in Indonesia. Not many studies have been conducted to measure the achievement of student learning outcomes, especially related to measurement skills and measurement uncertainty. Specifically, the purpose of this study is to investigate the knowledge of freshmen students who will become science teachers about measurement uncertainty in physics (science). Assessment and evaluation of measurement ability and measurement uncertainty are very important in laboratory skills for students in STEM fields in general. The relevance of this research is to attempt filling the gap; students may not go well through their scholastic and professional careers in STEM without an important scientific competency, such as measurement skills and its uncertainty. In addition, there are not many studies that measure the ability of freshmen students from education study programs in terms of measurement and measurement uncertainty.

2. METHOD

This study applied teacher research or self-study (Fraenkel et al., 2023). The research design we used was a one-group pre- and post-test design with interventions during the learning process (Betul Cebesoy & Karisan, 2020). The intervention was in the form of learning flexibility by combining practical activities (real laboratory and simulation) and concepts in General Physics Course. This study involved 25 first-year students in a science teacher education study program at one of the universities in East Java. The participants involved in this study have given consent and all data are kept confidential according to the FAIR principle (Wilkinson et al., 2016). The instrument used in this study was the Physics Measurement Questionnaire (PMQ) (Allie et al., 1998; Buffler et al., 2001; Pollard, Werth, et al., 2020). Four categories or indicator in PMQ were investigated in this study, namely (a) “repeated distance”-RD, (b) “using repeats”-UR, (c) “same mean different spread”-SMDS, and (d) “different mean same spread”-DMSS. All categories derive their foundation from Pollard et al.’s new PMQ codebook (Pollard, Hobbs, et al., 2020; Pollard, Werth, et al., 2020). The PMQ instrument was validated at a large-scale international level with the second highest validation or silver research validation category (5-6 categories) (*PhysPort Assessments*, n.d.).

Results In line with the new codebook, the data from the PMQ were assessed in four, different areas by Pollard et al. (Pollard, Hobbs, et al., 2020; Pollard, Werth, et al., 2020). These four areas were employed to assess the success of the intervention using normalized gain (Bao, 2006; Christman et al., 2024; Hake, 1998). Ultimately, the success of the intervention was gauged with a mean difference test and effect size according to the pretest and posttest scores. In order to account for the possible errors in the results of these inferential statistical tests (Benjamin & Berger, 2019;

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Sellke et al., 2001), the Vovk-Sellke Maximum p-ratios or VS-MPR will be computed and reported. The higher the VS-MPR result, the lesser effect the errors have on the results of the statistical significance of the mean difference test. Cohen's *d* effect size is typically characterized into three: small, moderate, and large (R. Wei et al., 2019).

3. RESULTS AND DISCUSSION

Based on the data from the intervention's results, learning flexibility was implemented in the General Physics Course by integrating practical exercises and concepts. The majority of freshmen or first-year students reported improvements in their understanding of measurement and its uncertainty. It is likely due to the intervention throughout the course. These teaching methods helped teachers clarify the concepts by allowing students to engage with combining practical activities (real laboratory and simulation) and concepts, which in turn deepened their comprehension of how to accurately measure quantities and account for uncertainties. According to the PMQ instrument, the process of increasing freshmen learning outcomes is classified into four categories: RD, UR, SMSD, and DMSS. According the test result, the normalized gain (<*g*>) distribution of freshmen students' learning outcomes related to measurement and its uncertainty is presented in Figure 1.

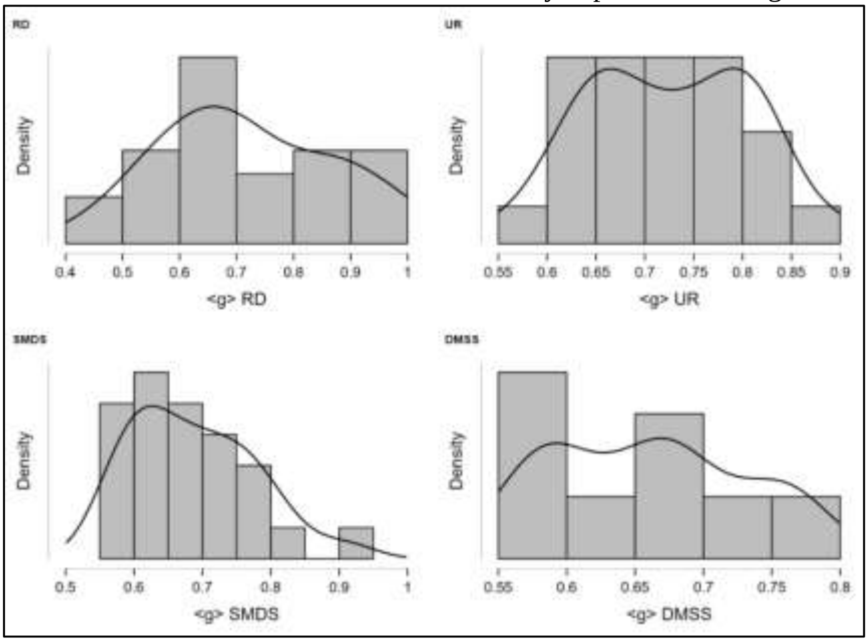

Figure 1. Distribution of <*g*> Freshmen's Learning Outcomes

Based on the data in Figure 1, it appears that first-year students have successfully improved their learning outcomes in the RD and UR categories, followed by the SMSD and DMSS categories. In the RD category, first-year students have been able to realize that repeated measurements are needed to minimize the error or uncertainty of the average measurement results, and are able to identify outliers from the dataset of measurement results. In the UR category, first-year students have been able to master that if the data distribution is relatively small, then writing the measurement results can use the average value. In addition, in the UR category, they must also report the average and uncertainty and range of the measurement data obtained. In the SMDS category, first-year students have been able to distinguish measures of data distribution that can affect uncertainty caused by external factors such as data outliers, human error, and other factors. In the DMSS category, some first-year students still experience problems related to datasets that have the same range, but different mean values. First-year students are still not well articulated regarding the similarity of mean values and ranges and how to analyze the overlap between the mean values and/or distribution of two datasets as well as how to use statistics in determining the accuracy of measurements. These results are in line with previous research: students frequently overlook measurement uncertainty, leading to flawed conclusions in laboratory settings, and despite recognizing the importance of uncertainty, they also struggle to apply their understanding of measurement uncertainty effectively in practical scenarios (Lu et al., 2023; Wan, 2023). Despite their reasoning improving, they still have problems with some scenarios (case of DMSS) (Werth, Pollard, et al., 2023).

In general, more than 50% of freshmen obtained <*g*> at a high level for RD and UR categories. On the other hand, in the SMDS and DMSS categories, more than 50% of freshmen obtained <*g*> at a medium level. No first-year students obtained <*g*> at a low level for RD, UR, SMDS, and DMSS categories. This suggests that the intervention process can change students' paradigms regarding measurement and its uncertainty (Pollard, Hobbs, et al., 2020; Pollard, Werth, et al., 2020). In general, the use of learning flexibility between practical activities and concepts can help first-year students to articulate substantive and procedural concepts as well as hand-on, mind-on, and heart-on activities together (Inan & Inan, 2015; Kota et al., 2019; Lee & Hong, 2024). This learning process also emphasizes the activity of reviewing the results of laboratory practice reports conducted by first-year students. The emphasis on experimental activities also enhances reasoning and the development of habits of mind and strategies in students (Holmes & Lewandowski, 2020; Wilcox & Lewandowski, 2017).

If viewed from a macro perspective, then based on the results of PMQ scores before and after the intervention, the effectiveness of the intervention carried out during self-study can be analyzed. Data normality testing, based on the difference between posttest and pretest. The results of data normality testing are presented in Figure 2. Based on the data in Figure 2, it is known that the difference between posttest and pretest scores is normally distributed (*AD* = 0.450; *p-value* = > 0.05). The data distribution is also entirely within the confidence interval (CI: 95%). These results then informed inferential statistical tests to determine statistical differences and the effectiveness of the intervention. The appropriate inferential statistical test to test the difference between the posttest and pretest results is the t-test. The t-test results based on the data in Table 1, showed that there was a statistical difference from the mean of the posttest to the posttest (*t* = 63.645; *p-value* = <0.05). This result corroborates the improvement of first-year students' learning outcomes related to measurement and its uncertainties. In order to minimize the bias factor due to errors that might affect the results of the t-test, it is necessary to test the *p-value*. The results of testing the t-test's *p-value* based on the VS-MPR value concluded that there is a small chance that errors affect the significance of the *p-value*. A large VS-MPR value indicates that the chance of the significance of the *p-value* being affected by errors is very small ($4.071 \times 10^{+25}$). The VS-MPR is more likely to favor the alternative hypothesis than the distinct hypothesis, validating the interpretation of the p-value (Benjamin & Berger, 2019).

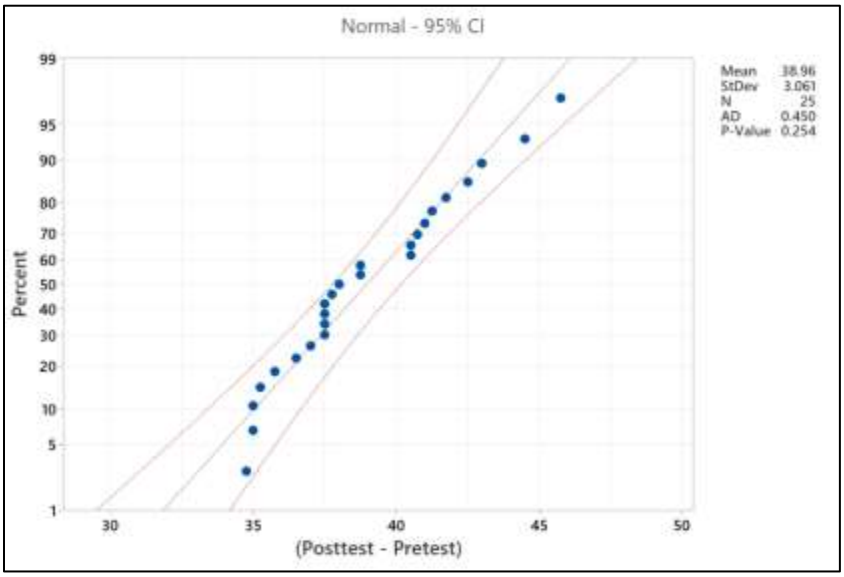

Figure 2. Probability Plot of Posttest Minus Pretest

Table 1. Paired Samples t-test Result

Data	*t*	*df*	*p*-*value*	VS-MPR*	Cohen's *d*	SE Cohen's *d*
Posttest – Pretest	63.645	24	< .001	$4.071 \times 10^{+25}$	12.729	1.540

Note. For all tests, the alternative hypothesis specifies that Posttest is greater than Pretest. *Vovk-Sellke Maximum *p* -Ratio: Based on a two-sided *p* -value, the maximum possible odds in favor of H_1 over H_0 equals 1/(-e *p* log(*p*)) for $p \leq .37$ (Sellke et al., 2001).

The effectiveness of the intervention in changing the paradigm and insight of first-year students about measurement and its uncertainty can also be seen from the effect size. Based on the Cohen's *d* value in Table 1, it is concluded that the Cohen's *d* value ≥ 0.5 (R. Wei et al., 2019) which means that there is a large effect size of the intervention. Visualization of the difference between posttest and pretest which resulted in a significant difference in mean scores and a large effect size as well as normalized gain which was at high criteria for the RD and UR categories, and moderate criteria for SMDS and DMSS is presented in Figure 3. Raincloud plots can visually represent raw data, probability size, and important summary statistics (Allen et al., 2021). Raincloud plots of posttest and pretest data in Figure 3 further strengthen interpretation and minimize bias based on normalized gain, t-test, and Cohen's *d* effect size (Christman et al., 2024; Coletta & Steinert, 2020). The intervention in self-study that has been carried out in the form of learning flexibility by combining practical activities and concepts in General Physics Course shows effective and promising results for course transformation in the first year at the higher education level.

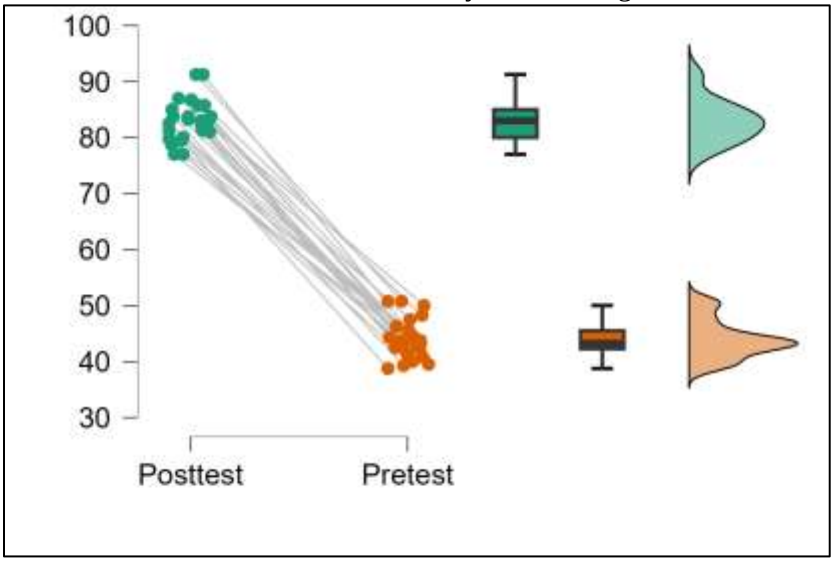

Figure 3. Raincloud Plot of Posttest and Pretest

The transformation of education and learning that is currently the mainstream of global higher education must also receive attention from Higher Education Institutions in Indonesia. Learning related to laboratory skills is also undergoing transformation in response to technological developments, industry demands, career diversification and alignment of student and graduate views, as well as renewed focus from researchers (Holmes & Lewandowski, 2020; Sulaiman et al., 2023). The laboratory-based education process is not only about "doing inquiry," but also emphasizes aspects of the process of science and the use of scientific method differentiation as a unity of scientific practice skills (Mutlu, 2020; Tran et al., 2018; B. Wei et al., 2022). In addition, we must emphasize or reconnect between the history of science and procedural learning, like how teachers used scientist's laboratory notes or historical experiment data when teaching students about measurement and its uncertainty (Thomas Becker et al., 2024), and the teacher helps in guiding students to establish their trajectory of sensemaking and adopt a model-based view of measurement as integrated into scientific investigation practice (Ha et al., 2024; Tang et al., 2024). Transformation of the learning process in first-year students' courses based on self-study or teacher research is needed with connection to the practice of sciences. Scaffolding, the role of the educator, and the design of learning activities are critical to ensure that first-year students can use scientific inquiry skills and are able to collaborate in the classroom (Davidson et al., 2022; Penn & Ramnarain, 2022; Soysal, 2022; Werth, West, et al., 2023).

4. CONCLUSION

Based on the results of the study, it was found that the interventions applied during self-study or teacher research for basic measurement and uncertainty determination skills (RD and UR categories) experienced high improvement, while those for higher skills (SMDS and DMSS categories) were at a moderate level. Overall, based on the normalized gain analysis, t-test, VS-MPR, Cohen's d effect size, and raincloud plot, it can be concluded that after the intervention, the first-year students managed to improve their insights and learning outcomes related to measurement and its uncertainties. This result reinforces that the experience and laboratory skills, or scientific inquiry skills, acquired in secondary school are relatively minimal and not yet solid. This further strengthens the need to evaluate the learning process for freshmen in educational study programs by re-designing learning activities and providing space for students to be actively involved in the authentic inquiry process. This is important in order to obtain future teachers who are able to design and transform learning in a sustainable manner.

REFERENCES

Allen, M., Poggiali, D., Whitaker, K., Marshall, T. R., Van Langen, J., & Kievit, R. A. (2021). Raincloud plots: A multi-platform tool for robust data visualization. *Wellcome Open Research*, *4*, 63. https://doi.org/10.12688/wellcomeopenres.15191.2

Allie, S., Buffler, A., Campbell, B., & Lubben, F. (1998). First-year physics students' perceptions of the quality of experimental measurements. *International Journal of Science Education*, *20*(4), 447–459. https://doi.org/10.1080/0950069980200405

Allie, S., Buffler, A., Campbell, B., Lubben, F., Evangelinos, D., Psillos, D., & Valassiades, O. (2003). Teaching measurement in the introductory physics laboratory. *The Physics Teacher*, *41*(7), 394–401. https://doi.org/10.1119/1.1616479

Aubin, C., Bierowiec, J. C., & Saunders, J. (2024). A new unit of measurement for introductory physics lab. *American Journal of Physics*, *92*(6), 455–458. https://doi.org/10.1119/5.0159531

Bao, L. (2006). Theoretical comparisons of average normalized gain calculations. *American Journal of Physics*, *74*(10), 917–922. https://doi.org/10.1119/1.2213632

Benjamin, D. J., & Berger, J. O. (2019). Three recommendations for improving the use of *p* -values. *The American Statistician*, *73*(sup1), 186–191. https://doi.org/10.1080/00031305.2018.1543135

Betul Cebesoy, U., & Karisan, D. (2020). Teaching the role of forests in mitigating the effects of climate change using outdoor educational workshop. *Research in Science & Technological Education*, 1–23. https://doi.org/10.1080/02635143.2020.1799777

Buffler, A., Allie, S., & Lubben, F. (2001). The development of first year physics students' ideas about measurement in terms of point and set paradigms. *International Journal of Science Education*, *23*(11), 1137–1156. https://doi.org/10.1080/09500690110039567

Carter, A. R. (2021). One hundred years later, introductory labs are poised for change. *The Physics Teacher*, *59*(2), 97–99. https://doi.org/10.1119/10.0003460

Christman, E., Miller, P., & Stewart, J. (2024). Beyond normalized gain: Improved comparison of physics educational outcomes. *Physical Review Physics Education Research*, *20*(1), 010123. https://doi.org/10.1103/PhysRevPhysEducRes.20.010123

Coletta, V. P., & Steinert, J. J. (2020). Why normalized gain should continue to be used in analyzing preinstruction and postinstruction scores on concept inventories. *Physical Review Physics Education Research*, *16*(1), 010108. https://doi.org/10.1103/PhysRevPhysEducRes.16.010108

Davidson, S. G., Jaber, L. Z., & Southerland, S. A. (2022). Cultivating science teachers' understandings of science as a discipline. *Science & Education*, *31*(3), 657–683. https://doi.org/10.1007/s11191-021-00276-1

Dounas-Frazer, D. R., & Lewandowski, H. J. (2018). The modelling framework for experimental physics: Description, development, and applications. *European Journal of Physics*, *39*(6), 064005. https://doi.org/10.1088/1361-6404/aae3ce

El Masri, Y. H., Erduran, S., & Ioannidou, O. (2021). Designing practical science assessments in England: Students' engagement and perceptions. *Research in Science & Technological Education*, 1–21. https://doi.org/10.1080/02635143.2021.1872519

Fraenkel, J. R., Wallen, N. E., & Hyun, H. H. (2023). *How to Design and Evaluate Research in Education*. McGraw-Hill.

Ha, H., Chen, Y., & Park, J. (2024). Teacher strategies to support student navigation of uncertainty: Considering the dynamic nature of scientific uncertainty throughout phases of sensemaking. *Science Education*, *108*(3), 890–928. https://doi.org/10.1002/sce.21857

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, *66*(1), 64–74. https://doi.org/10.1119/1.18809

Han, C., & Xiang, J. (2024). Alignment analysis between China College Entrance Examination Physics Test and Curriculum Standard Based on E-SEC Model. *International Journal of Science and Mathematics Education*. https://doi.org/10.1007/s10763-024-10468-0

Holmes, N. G., & Lewandowski, H. J. (2020). Investigating the landscape of physics laboratory instruction across North America. *Physical Review Physics Education Research*, *16*(2), 020162. https://doi.org/10.1103/PhysRevPhysEducRes.16.020162

Holmes, N. G., & Wieman, C. E. (2018). Introductory physics labs: We can do better. *Physics Today*, *71*(1), 38–45. https://doi.org/10.1063/PT.3.3816

Inan, H. Z., & Inan, T. (2015). 3 H s Education: Examining hands-on, heads-on and hearts-on early childhood science education. *International Journal of Science Education*, *37*(12), 1974–1991. https://doi.org/10.1080/09500693.2015.1060369

Kota, S. D., Cornish, S., & Sharma, M. D. (2019). Switched on! Student and teacher engagement in an electricity practical. *Physics Education*, *54*(1), 015007. https://doi.org/10.1088/1361-6552/aadeee

Kuang, X., Eysink, T. H. S., & Jong, T. (2020). Effects of providing partial hypotheses as a support for simulation-based inquiry learning. *Journal of Computer Assisted Learning*, *36*(4), 487–501. https://doi.org/10.1111/jcal.12415

Lee, G.-G., & Hong, H.-G. (2024). Development and validation of the blended laboratory and e-learning instructional design (BLEND) model for university remote laboratory sessions: Responding to the COVID-19 pandemic and planning for the future. *Educational Technology Research and Development*, *72*(2), 1025–1065. https://doi.org/10.1007/s11423-023-10327-9

Lu, C., Liu, Y., Xu, S., Zhou, S., Mei, H., Zhang, X., Yang, L., & Bao, L. (2023). Conceptual framework assessment of knowledge integration in student learning of measurement uncertainty. *Physical Review Physics Education Research*, *19*(2), 020145. https://doi.org/10.1103/PhysRevPhysEducRes.19.020145

Mandavgade, N. K., Jaju, S. B., Lakhe, R. R., & Tidke, D. J. (2012). Need and difficulties in uncertainty of measurement. *International Journal of Measurement Technologies and Instrumentation Engineering*, *2*(3), 23–33. https://doi.org/10.4018/ijmtie.2012070103

Mutlu, A. (2020). Evaluation of students' scientific process skills through reflective worksheets in the inquiry-based learning environments. *Reflective Practice*, *21*(2), 271–286. https://doi.org/10.1080/14623943.2020.1736999

Penn, M., & Ramnarain, U. (2022). South African Grade 12 science students' understandings of scientific inquiry. *Science & Education*, *31*(3), 635–656. https://doi.org/10.1007/s11191-021-00259-2

PhysPort Assessments: Physics Measurement Questionnaire. (n.d.). PhysPort. Retrieved October 8, 2024, from https://www.physport.org/assessments/assessment.cfm?A=PMQ

Pollard, B., Hobbs, R., Dounas-Frazer, D. R., & Lewandowski, H. J. (2020, January 13). Methodological development of a new coding scheme for an established assessment on measurement uncertainty in laboratory courses. *2019 Physics Education Research Conference Proceedings*. 2019 Physics Education Research Conference, Provo, UT. https://doi.org/10.1119/perc.2019.pr.Pollard

Pollard, B., Werth, A., Hobbs, R., & Lewandowski, H. J. (2020). Impact of a course transformation on students' reasoning about measurement uncertainty. *Physical Review Physics Education Research*, *16*(2), 020160. https://doi.org/10.1103/PhysRevPhysEducRes.16.020160

Sellke, T., Bayarri, M. J., & Berger, J. O. (2001). Calibration of ρ values for testing precise null hypotheses. *The American Statistician*, *55*(1), 62–71. https://doi.org/10.1198/000313001300339950

Smith, E. M., & Holmes, N. G. (2021). Best practice for instructional labs. *Nature Physics*, *17*(6), 662–663. https://doi.org/10.1038/s41567-021-01256-6

Soysal, Y. (2022). Middle school science teachers' discursive purposes and talk moves in supporting students' experiments. *Science & Education*, *31*(3), 739–785. https://doi.org/10.1007/s11191-021-00266-3

Sulaiman, N., Werth, A., & Lewandowski, H. J. (2023). Students' views about experimental physics in a large-enrollment introductory lab focused on experimental scientific practices. *Physical Review Physics Education Research*, *19*(1), 010116. https://doi.org/10.1103/PhysRevPhysEducRes.19.010116

Tang, X., Shu, G., Wei, B., & Levin, D. (2024). Emergent learning about measurement and uncertainty in an inquiry context: A case from an elementary classroom. *Science Education*, *108*(1), 308–331. https://doi.org/10.1002/sce.21837

Thomas Becker, M. H., Heidemann, L. A., & Lima, N. W. (2024). History of science in physics education in the last decade: Which direction we are heading? *Science & Education*. https://doi.org/10.1007/s11191-024-00537-9

Tran, T.-B., van den Berg, E., Ellermeijer, T., & Beishuizen, J. (2018). Learning to teach inquiry with ICT. *Physics Education*, *53*(1), 015003. https://doi.org/10.1088/1361-6552/aa8a4f

Vignal, M., Geschwind, G., Pollard, B., Henderson, R., Caballero, M. D., & Lewandowski, H. J. (2023). Survey of physics reasoning on uncertainty concepts in experiments: An assessment of measurement uncertainty for introductory physics labs. *Physical Review Physics Education Research*, *19*(2), 020139. https://doi.org/10.1103/PhysRevPhysEducRes.19.020139

Walsh, C., Quinn, K. N., Wieman, C., & Holmes, N. G. (2019). Quantifying critical thinking: Development and validation of the physics lab inventory of critical thinking. *Physical Review Physics Education Research*, *15*(1), 010135. https://doi.org/10.1103/PhysRevPhysEducRes.15.010135

Wan, T. (2023). Investigating student reasoning about measurement uncertainty and ability to draw conclusions from measurement data in inquiry-based university physics labs. *International Journal of Science Education*, *45*(3), 223–243. https://doi.org/10.1080/09500693.2022.2156824

Wei, B., Jiang, Z., & Gai, L. (2022). Examining the nature of practical work in school science textbooks: Coverage of the diversity of scientific methods. *Science & Education*, *31*(4), 943–960. https://doi.org/10.1007/s11191-021-00294-z

Wei, R., Hu, Y., & Xiong, J. (2019). Effect size reporting practices in applied linguistics research: A study of one major journal. *SAGE Open*, *9*(2), 215824401985003. https://doi.org/10.1177/2158244019850035

Werth, A., Pollard, B., Hobbs, R., & Lewandowski, H. J. (2023). Investigating changes in student views of measurement uncertainty in an introductory physics lab course using clustering algorithms. *Physical Review Physics Education Research*, *19*(2), 020146. https://doi.org/10.1103/PhysRevPhysEducRes.19.020146

Werth, A., West, C. G., Sulaiman, N., & Lewandowski, H. J. (2023). Enhancing students' views of experimental physics through a course-based undergraduate research experience. *Physical Review Physics Education Research*, *19*(2), 020151. https://doi.org/10.1103/PhysRevPhysEducRes.19.020151

Wilcox, B. R., & Lewandowski, H. J. (2017). Developing skills versus reinforcing concepts in physics labs: Insight from a survey of students' beliefs about experimental physics. *Physical Review Physics Education Research*, *13*(1), 010108. https://doi.org/10.1103/PhysRevPhysEducRes.13.010108

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., Da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., … Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, *3*(1), 160018. https://doi.org/10.1038/sdata.2016.18