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The Digital Pipetting Badge: A Method To Improve Student Hands-On Laboratory Skills

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ABSTRACT: An evidence centered design approach was used to develop, implement, and assess a novel and innovative digital pipetting badge using Purdue's Passport system. Each student in a large lecture course created a video demonstrating how to use a 10 mL pipet to dispense liquid. The video was uploaded into the Passport system, which allowed instructors to give each student feedback on their pipetting technique and to either accept or deny the video. Students who had denied videos were able to use the feedback to improve their technique, reshoot the video, and upload it again for grading. Student perceptions of their knowledge, confidence, and experience pipetting were collected before and after the laboratory where the videos were created. Analysis demonstrated significant differences in student perceptions and large effect sizes. Over 90% of students correctly answered a multiple-choice item on the first exam and the final pertaining to the process of pipetting. The digital pipetting badge significantly and positively impacted classroom practices wherein the students learned to pipet more effectively and improved their knowledge, confidence, and experience in pipetting.

KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, Laboratory Instruction, Hands-On Learning/Manipulatives, Laboratory Equipment/Apparatus, Chemical Education Research, Testing/Assessment*

FEATURE: Chemical Education Research

Pipetting is a fundamental skill used routinely in general chemistry courses nationwide in which a solution is suctioned into a calibrated glass tube in order to measure precise volumes of solutions. To pipet, a student needs two pieces of equipment, a pipet and a pipet bulb. According to staff in Purdue's preparations laboratory that prepare all chemicals and manage equipment for the laboratories, the chemistry department purchases 200−250 pipet bulbs each semester at a cost of $14 each. Thus, the department spends $2800−$3500 each semester on a single type of equipment. Through improper use the students render many of the bulbs useless (we could list the ways in which this happens, but it is easier to acknowledge that it happens). Though each laboratory textbook contains an appendix describing in detail how to properly fill and deliver a sample of liquid using a pipet and pipet bulb, students unintentionally misuse the bulbs, and as a result, the department loses equipment.

Beyond the damage caused to equipment, improper pipetting undermines the students' educational experience. Many of the experiments that students carry out require them to form conclusions and elaborate their chemical knowledge based on the data from their lab experiments. But when the students measure the volumes of their solutions incorrectly, the students' subsequent calculations become less precise, less accurate, more random, and the data are robbed of their meaning. Instead of drawing the intended conclusions, students learn that they cannot trust their data and are prevented from carrying out authentic science practices. Instead of illustrating how concepts and theories can be derived from data, laboratory coursework becomes a series of steps to carry out, disconnected from the science content.

This loss of equipment and loss of educational opportunity does not stem from malevolence or indifference. The manipulation of the equipment requires coordination and dexterity obtained through extensive practice; to correctly carry out the technique requires deliberate rehearsal and coaching. Many students are intimidated by the technique and avoid using it altogether because they incorrectly believe alternate techniques will provide equivalent results. Because verbal instructions and written guidelines provided in the classroom have been insufficient at overcoming these obstacles, we partnered with the instructional technology staff associated with Purdue's Passport[1] system in spring 2014 to develop and implement a digital badge to improve pipetting skills, knowledge, and confidence with the technique.

Badging as a way to showcase competence or skills is not new; the Boy Scouts of America and Girl Scouts of the USA have used such credentials to represent the judgment of the organization about the person's knowledge, skills, or qualifications. Academic,

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professional, and volunteer organizations such as medical boards, bar associations, and the National Ski Patrol[2] have participated in credentialing as well. The distinction of a digital badge is that it contains information online about the issuer, the specific activities required to earn the badge, the criteria used to evaluate badge activities, and the evidence: the performance or artifact.[3] The badge serves as documentation of learning when it is grounded in evidence-based inferences about the knowledge and skills associated with badging activity.[4] Digital badging is an important form of assessment that ties more closely to learning theories than many other methods of skill assessment. Indeed, it could be argued that undergraduate laboratory skills are so poorly and/or infrequently assessed that students receive a message that the skills are not valued.[5−9] We believe that digital badging offers a novel and innovative way to assess laboratory skills.

At Purdue University, the Passport[1] system allows students to visually display their work as a product of their procedural knowledge. It is a powerful way to assess a hands-on laboratory technique with an evidence-centered approach.[10,11] Assessment of a student's video carrying out a technique offers several benefits. It allows students to demonstrate their learning and to receive individualized feedback on their performance. It also ensures that students are carrying out the techniques as intended in order to obtain the maximum educational impact from the laboratory experiments. The Passport system provides access to these benefits of assessment by relieving the time constraints that prevent the instructors from evaluating each student within the laboratory period.

■ LITERATURE

Learning in the Undergraduate Chemistry Laboratory and Assessing Hands-On Laboratory Skills

Undergraduate teaching laboratories play an important role in science education.[6,12−19] Nakhleh, Polles, and Malina[6] in 2002 wrote, "Laboratory work is an integral component of learning chemistry (or any science)" (p 69) that "has been almost universally regarded as desirable, if not essential" (p 72). However, concerns remain about the goals of laboratory instruction.[8,15,16,19−24]

Beginning in 2005, the Towns research group, in conjunction with the Bretz group at Miami University, embarked on an NSF-funded research project to identify faculty goals for undergraduate laboratory. One of the goals that emerged across the undergraduate chemistry curriculum was the development of hands-on laboratory skills.[25] Findings from a national survey of 319 chemistry faculty regarding their goals for undergraduate chemistry laboratory courses also supported the development of hands-on skills within the context of the development of "research skills" and "transferable skills" which are specific to laboratory.[26] Additionally, Reid and Shah[8] cited "practical skills" as a specific aim of undergraduate chemistry laboratories. However, research into appropriate or innovative assessment methods of hands-on laboratory skills is lacking.

We have continued our research by investigating student goals for laboratory in an effort to discern the ways in which faculty and student goals for laboratory correspond to one another and the implications for the laboratory curriculum. Through video recordings of students carrying out laboratory experiments and a subsequent interview with each student, we have evaluated the hands-on laboratory skills of first-year general chemistry students pursuing various majors and junior and senior level chemistry majors taking analytical chemistry.[27] We have found evidence that regardless of their intended major or level of experience, students thwart the faculty goal of learning laboratory skills by dividing laboratory tasks among group members. The student who is most likely to carry out a hands-on skill such as pipetting, making solutions in volumetric flasks, using burets, or obtaining spectroscopic data is the student who is most confident in his or her ability to do so (regardless of the student's actual ability to perform the technique).

Upon the basis of the literature on learning in undergraduate chemistry laboratory and our group's ongoing research, it is clear that a need exists to develop evidence-centered methods of assessing hands-on laboratory skills that lead to improved self-efficacy for students and improved accuracy and precision of student laboratory techniques. Additionally, there is a need to establish the durability of hands-on laboratory skill for future coursework.

Digital Badges and Evidence Centered Design

Digital badges are a method of showcasing a learner's earned skills or competencies in education.[3] The idea of utilizing a visual representation of achievement is not new, but the idea of utilizing it as a credential model is one that is currently emerging. Digital badges allow instructors to create measurable course outcomes and explicitly tracked tasks and activities for completion by a student. The information attached to the badge is specific and includes explicit metadata about the issuer (the who), criteria (the what), and evidence (the how).

The assessments associated with the activities that are part of the badging process must be grounded in evidence-based inferences about knowledge, skills, and attitudes so that the badge is representative of student learning. An evidence-based design approach[10,11] facilitates this grounding using the following core questions and constructs: what are the knowledge, skills, and attitudes connected to undergraduate chemistry laboratory that should be assessed, and what tasks would allow a student to demonstrate those constructs?[28] In practice, the framework suggests three steps: collection of student work/artifacts, evaluation of the work/artifacts relative to agreed upon criteria that are grounded in analysis and modeling of the domain, and creation of inferences based upon the quality of the student's work.

A recent report on STEM Badges[4] identified six directions for future research including assessment. As part of the future directions they called for identifying "processes for implementing valid and reliable badge-based assessments." Additionally, this report brings up the notion of "shelf life" or durability of a badge. The knowledge, skills, and attitudes represented by a badge pertaining to lab skills are likely to partially decay over time, especially if the knowledge, attitudes, and skills are not maintained or used in other venues. For example, if a group of students earn a badge in a particular hands-on laboratory skill, what is the decay over the semester, from one semester to the next, or over the summer? What might those different decay rates tell faculty about badge maintenance and renewal? In other words, how often and in what ways should badges pertaining to laboratory skills be renewed? The research is silent on this issue and if badging is to become part of the undergraduate chemistry laboratory landscape, then we need to know the answers to those questions, the durability represented by a badge, and how badging can be integrated into laboratory curricula to support sustained learning.

Connections Across Literature

Our prior research on learning in the undergraduate chemistry laboratory has allowed us to analyze the domain; particularly the goals faculty have for undergraduate laboratory. The key

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aspect we have chosen to focus on as we have modeled the domain of faculty goals are hands-on laboratory skills. Ultimately, students' lack of laboratory skills has the effect of limiting choices in content that may be included in curriculum design projects. If students cannot perform key laboratory tasks with fidelity, the extent of learning they can achieve in the laboratory is inherently limited by their skill set.

Digital badging has the potential to provide a method for the authentic and direct assessment of these laboratory skills. Purdue University has developed a learning management system called Passport[1] that uses an open badge infrastructure. It allows for instructors to create, assess, and award digital badges based on student completion of learning challenges. Passport was developed in 2012 and launched for both internal Purdue faculty and interested external entities in higher education through a trial request application.

Thus, at Purdue University, we have a unique opportunity to develop digital badges that hold the promise of assessing hands-on laboratory skills in a new and more authentic manner using an evidence-centered design. The claims we make about a student's hands-on skills will be based upon evidence-based inferences and will serve as documentation of learning.

Goal and Research Question

The overarching goal was to demonstrate that a digital pipetting badge could be developed and implemented in a large lecture course. Within that implementation, we collected and analyzed data that would allow us to determine the impact of the badging project through the following research question: In what ways does a digital pipetting badge impact students' hands-on laboratory skills?

■ THE DEVELOPMENT AND IMPLEMENTATION OF A DIGITAL PIPETTING BADGE

The team of faculty and staff that developed the digital pipetting badge consisted of chemists (Towns and Harwood), assessment specialists (Robertshaw and Towns), and instructional technology specialists (Fish and his staff). Initially, the group considered what elements would go into a digital pipetting badge including the steps students would follow when filming a video to provide evidence of good pipetting technique. Towns and Harwood developed the student instructions in Box 1 based upon best practices and the students' laboratory textbook to identify what the students needed to do and to demonstrate during filming.

Towns modified a Participant Perception Indicator survey from the literature which is described in the Methods section to assess students' knowledge, confidence, and experience.[29] Robertshaw led the team in the discussion of assessment of student learning and rubric development for grading. Fish and his team built the badge in the Passport environment, developed instructional materials for implementation in the classroom, and assisted students who were having trouble uploading their videos.

The digital pipet badge was piloted in 2014 with 24 students. The students filmed their pipetting videos at the end of the laboratory period (there was plenty of time at the end of lab to create the videos) in the same laboratory room with students supplying their own devices for filming. The videos were then uploaded through the Passport app for analysis. The key finding from the pilot was the importance of instructing the students to narrate their video: to tell the instructor what they were doing. Most pilot videos were silent after the students had stated their name and section number.

Box 1. Fall 2014 Student Instructions for Their Pipetting Video

Pipet Video Instructions (Remember to narrate, tell us what you are doing):

1. State your name at the beginning of the video.
2. State Laboratory Section number.
3. Your face and hands must be shown in the video at the beginning.
4. Collapse pipet bulb properly (not attached to pipet).
5. Connect bulb to pipet properly (tell us how).
6. Draw liquid into the pipet above mark, but not into the bulb.
7. Do a close-up shot showing the meniscus at calibration mark.
8. Remove drops of liquid from the end of pipet if needed by tapping on side of beaker.
9. Dispense liquid into flask.
10. Do a close-up shot showing the bottom 2−3 in. of pipet. There should still be liquid in the bottom.

In the fall of 2014, we implemented the digital pipet badge during the second experiment in a course of 974 students as a required activity worth 8 points out of 1000 points in the course. Students were first instructed to read their laboratory notebook describing how to properly pipet and then in the laboratory session, teaching assistants demonstrated how to use a pipet. After the students completed the experiment, each student created a video demonstrating his or her pipetting technique utilizing their own video device (a smartphone, tablet, or laptop computer for example). The filming took place in the laboratory classroom at the student's lab bench or in room where the balances are kept, and enough time was left in the class period for each student to create a video. There were no students who were unable to create a video due to a lack of a device and lab partners served as videographers. Students typically completed the video recording process of capturing their pipetting skills in roughly 2 min. After obtaining the video (some students reshot it if they were not happy with the outcome or if someone photo bombed), the students directly uploaded the video through the Passport app.

The badging activity was listed in the course syllabus, described in class, and posted on the course Web site. Fish's team created materials supporting student engagement and were available to trouble-shoot directly with students one-on-one to address any technology issues that emerged during the activity. The digital badging activity was open for 2 weeks so that students who missed lab in week two, or had their video denied, were able to film/refilm their video the following week and get it uploaded.

Once the videos were uploaded, graders used the Passport system to watch the videos, accept or deny them, and provide individualized feedback to each student. The videos ranged in length from 55 s to nearly 3 min, with the majority in the 1.5−2 min range. The grading rubric matched the instructions given to the students with the most salient points being collapsing the bulb before attaching it to the pipet, properly connecting the bulb and pipet, positioning the bottom of the meniscus at the calibration line, and allowing the liquid to flow out leaving a small amount in the tip of the pipet. Initially, evaluating a video and providing feedback took approximately 4−5 min. However, as more videos were graded, the time decreased by focusing on

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the parts of the video that corresponded to the rubric and using standardized statements as feedback.

■ METHODS

Class Context

The digital pipetting badge was implemented during the second and third weeks of Chemistry 11100, the general chemistry course taken predominately by students in the college of agriculture and college of health and human sciences. Upon the basis of Fall 2012 survey data, 30% of the nearly 1000 students in Chemistry 11100 have carried out five or fewer chemistry laboratories in high school. Students come to the course without significant hands-on laboratory skills; thus, they need opportunities to become proficient at them to be successful in the course.

During the second week of the course, the students completed an experiment to acquaint them with how to measure mass and volume of liquids in the chemistry laboratory. The volume measurements were carried out with a variety of pieces of glassware (a beaker, a pipet, and a graduated cylinder) and the students analyzed their data to determine the most accurate piece of glassware. Within the context of this experiment, the students learned how to use a volumetric pipet to measure liquids. Subsequently, this skill was used in 6 of 10 wet experiments during the 16-week course.

Data Collection

To measure student perceptions, we modified a Participant Perception Indicator survey from the literature.[28] The items were designed to measure the impact of the pipetting experience on the students' perception of their knowledge, confidence, and ability to pipet. The instrument is based upon self-efficacy[30] and focuses on what the students *can* do using two identification statements and five process statements as shown in Table 1. For each item the student was asked to respond separately on a five-point Likert scale for knowledge (cognitive dimension), experience (psychomotor dimension), and confidence (affective dimension). Prior to each survey the students were given a sample item about making a cup of tea to demonstrate how the scales were operationalized.

Table 1. Seven Statements To Measure Students' Knowledge, Experience, and Confidence Pipetting

Statement	Knowledge[a,b]	Experience[a,b]	Confidence[a,b]
1. Identify a pipet from among pieces of glassware.	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
2. Identify a pipet bulb from among pieces of equipment.	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
3. Use a pipet and pipet bulb to deliver a sample of liquid to a flask.	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
4. Connect a pipet and pipet bulb properly.	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
5. Draw liquid into a pipet.	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
6. Get liquid to the proper level in the pipet.	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
7. Dispense liquid from the pipet.	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

[a]The scale ranges from a low score of 1 to a high score of 5. [b]The maximum score for each subscale is 35.

The instrument was administered three times online within the Passport system as part of the badge activity. The first was a pretest to be completed prior to the second laboratory. The next two surveys were completed after the laboratory. After submitting a video, a student then completed a "retrospective" prelab survey that allowed a student to think back to before they had completed the lab to reconsider what he or she did and did not know about pipetting.[31−33] The notion behind the retrospective survey was that students might not really know what they did not know until after they had completed the video portion of the badge activity and it is a way to control for response shift bias.[34] Finally, the students completed the postlab survey. The retrospective prelab survey and postlab survey were closed 2 weeks after the laboratory and all survey data was downloaded for analysis. This research design allowed us to measure student knowledge, experience, and confidence before and after the laboratory.

A multiple-choice question pertaining to the process of pipetting was given on the first exam at week five in the course and on the final exam.

Data Analysis

Descriptive statistics were determined from the survey data and paired samples t tests between Pre−Retrospective Pre, Pre−Post, and Retrospective Pre−Post were carried out. Where significant differences were found, a Cohen's effect size was calculated.[35] While p-values can identify whether a significant difference exists, Cohen's effect size values reveal the size of the effect.

Using Chronbach's α, we determined that the reliability of the scale across the three subscales was high ($\alpha = 0.971$). Though this could be regarded as too high, the level of reliability is acceptable because of the narrow scope of the content being covered, as well as the repetition of the seven items across each self-efficacy domain.[36] Factor analysis was carried out using principal components analysis and a direct oblimin rotation.[37] The results demonstrated that all 21 items loaded on the same factor indicating that the items are highly correlated. The items have curricular validity because they align with the instructions in the laboratory manual and knowledge that the students must have in identifying pieces of equipment in order to pipet. Finally, they have high face validity being derived from best practices in chemistry laboratories and being vetted by chemistry faculty and chemistry education researchers.

The percentage correct for the multiple-choice question on the topic of pipetting on the first exam and final exam were calculated.

■ RESULTS

The digital pipetting badge was implemented in Fall 2014 in Chemistry 11100 with 965 students, 874 of whom submitted videos and 843 of whom completed all surveys and submitted a video. There was a large improvement in students' self-reported confidence in, experience with, and knowledge of pipetting skills as shown by the increasing means in Table 2. All comparisons between means on pre−post, retrospective pre−post, and pre−retrospective pre surveys for confidence, experience, and knowledge are statistically significant ($p < 0.001$) and an effect size was calculated for each comparison. The effect size describes how different the groups are rather than just if they are different and is not influenced by sample size. The range for effect sizes of 0−0.30 is considered small, 0.3−0.6 medium, and 0.6 and above is large.[35] The Cohen's effect size values shown in Table 3 suggest a moderate to high practical significance. The analysis establishes that students improved their knowledge, confidence, and experience in being able to identify a pipet and a pipet bulb, and in the ability to carry out the procedure of pipetting. Among the individual statements shown in Table 1,

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Table 2. Descriptive Statistics for Each of the Subscales for Each Survey

Scale	Measurement	Mean	Std. Dev.
Confidence	Pre	23.23	6.29
	Retrospective Pre	26.64	4.35
	Post	34.48	2.22
Experience	Pre	20.46	7.14
	Retrospective Pre	29.14	6.58
	Post	33.42	4.24
Knowledge	Pre	22.92	6.46
	Retrospective Pre	31.09	5.34
	Post	34.60	2.06

Table 3. Effect Sizes for Comparisons between Each Survey

Subscale	Survey Comparison	Effect Size for Comparison	Small/ Medium/Large Effect Size
Confidence	Post−Pre	2.38	Large
	Post−Retrospective Pre	2.27	Large
	Pre−Retrospective Pre	0.63	Large
Experience	Post−Pre	2.21	Large
	Post−Retrospective Pre	0.77	Large
	Pre−Retrospective Pre	1.26	Large
Knowledge	Post−Pre	2.44	Large
	Post−Retrospective Pre	0.86	Large
	Pre−Retrospective Pre	1.38	Large

the largest gain between the pre−post surveys and for the retrospective pre−post surveys was for knowledge, experience, and confidence was on the statement "Connect a pipet and pipet bulb properly."

Results from the Examination Questions

After completing the digital pipetting badge, the students were asked a procedural question pertaining to pipetting on the first exam and on the final using newly created exam items. The exam 1 multiple-choice item asked students to identify where in a 10 mL pipet the meniscus should be located. To answer this question correctly, the student would need to know the appropriate location of the meniscus with respect to the calibration line. On this item, 912 out of 965 students, or 94.5%, answered the question correctly. On the final exam, the item contained a picture of a 5 mL pipet where the liquid had been drawn above the calibration line. The students would need to evaluate the picture, recognize that the meniscus was above the calibration line, and that it needed to be lowered in order to accurately deliver 5 mL of sample. On this item, 909 out of 928, or 98%, of the students chose the correct answer. The significance of the scores on the examination questions is twofold: the demonstration of correct knowledge about pipetting and the retention of that knowledge across the semester.

■ DISCUSSION

There are multiple methods of demonstrating the impact on student learning with this digital pipetting badge.

- The videos are the key artifact from which inferences about student learning can be made. They allowed students to receive direct feedback on their pipetting technique. Further, students could make use of the feedback and improve their technique by refilming their video and uploading it for grading.
- The survey data yielded significant differences between every survey pair (pre−post, retrospective pre−post and pre−retrospective pre) and large effect sizes. These large effect sizes are particularly compelling pieces of evidence that students perceive much greater knowledge, confidence, and experience in identifying a pipet and a pipet bulb, and in their procedural knowledge, confidence, and experience in pipetting a sample of a liquid.
- Exam 1 and Final Exam results demonstrated that 94.5% and 98% of the students could correctly answer a procedural question about pipetting and that the knowledge was retained.

Experienced graduate teaching assistants also commented to us that the students were more competent in their pipetting technique in subsequent labs than in previous years. One commented that usually she would be asked to teach pipetting technique repeatedly during the semester, but after the implementation of the pipetting badge, the students knew what they were doing and did not ask. One student commented on the anonymous course evaluation: "*At first I thought the pipetting badge assignment was stupid, but later I realized how important being able to pipet efficiently is.*"

We also were able to collect and analyze data that demonstrated this digital badging approach is effective for students with disabilities. A student with visual impairment narrated her entire video and was able to carry out steps 1−5 in Box 1; at this point, her assistant drew the liquid to the calibration line, and then the student finished the remaining steps. A mobility-impaired student was also able to carry out the tasks to earn a digital pipetting badge. Thus, we have evidence that this digital badging activity is accessible to students with disabilities, a group that is underserved in STEM.

We have demonstrated that digital badging using Purdue's Passport system is a novel and innovative method of assessing and improving student pipetting skills. This report establishes that digital badging can be implemented in large lecture courses providing a method of furnishing students individual feedback on their laboratory technique. For chemistry education research, it ushers in a new area of assessment research emphasizing an evidence-based approach that can lead to more authentic assessments and the possibility of deconvoluting the assessment of hands-on laboratory skills from laboratory learning.

Reflections of Instructors

The strength of the digital badging system was that it allowed instructors and graduate teaching assistants to evaluate an authentic piece of evidence from a student that directly demonstrates the student's ability to carry out the technique. For students who engaged in practices that were improper or unsafe (jamming the pipet into the pipet bulb much too far), we provided feedback in the Passport system and in some cases reached out to students during their laboratory period to provide one-on-one coaching and feedback. The digital badge allowed us to uniquely identify students who needed one-on-one coaching to improve their technique.

Limitations

The measurement of students' knowledge, confidence, and experience of laboratory skills provided by the PPI surveys is dependent on student perceptions, not independent observations. However, the feedback on the student videos was an independent observation of student skill in the technique. The performance on the multiple-choice exam item on the final functions as a proxy for durability and could be enhanced by

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having the students repeat the creation of a pipet video for uploading and evaluation at the end of the semester.

CONCLUSIONS

The evidence provided by the student videos, analysis of survey data, and performance on examination questions establishes that the digital pipetting badge significantly and positively impacted classroom practices wherein the students learned to pipet more effectively and improved their knowledge, confidence, and experience in pipetting. We look forward to the development and implementation of other digital badges that hold the promise of improving students' hands-on laboratory skills.

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Notes

The authors declare no competing financial interest.

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