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Is this Solution Pink Enough? A Smartphone Tutor to Resolve the Eternal Question in Phenolphthalein-Based Titration

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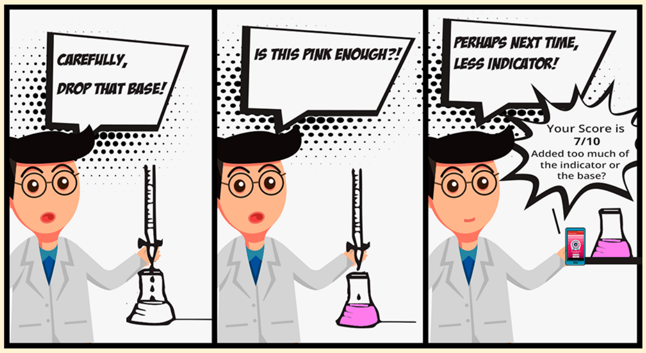
Supporting Information

ABSTRACT: "Is this solution pink enough?" is a persistent question when it comes to phenolphthalein-based titration experiments, one that budding, novice scientists often ask their instructors. Lab instructors usually answer the inquiry with remarks like, "Looks like you have overshot the end point", "Perhaps you should check the amount of the indicator and redo", and "The pink can be fainter." However, in a large classroom setting, it often becomes tedious for teachers to provide personalized remarks to students on their titration conduct at frequent intervals. In an effort to get the learners to become independent in evaluating their titration experiments, in this paper, the design, development, and implementation of a new smartphone tutor application named Titration Color-Darts (TCD) has been presented. TCD uses the camera function to analyze the pink color of the titration solution to provide learners with a feedback report on their experimental conduct. TCD maps the gradient of pink (from light to dark) to a corresponding performance score (on a scale of 1 to 10) and presents it in a gamified manner on a dartboard. It generates a report that includes question prompts and hints to elicit a learner's reasoning for independently identifying potential sources of error in their experiment and for figuring out how they can be resolved. The results from the initial pilot exercise conducted with undergraduate students corroborate the effectiveness of TCD as a lab tutor.



KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Laboratory Instruction, Computer-Based Learning, Problem Solving/Decision Making, Titration/Volumetric Analysis*

■ INTRODUCTION

The sensory nature of chemistry often serves as an anchor point to capture a student's attention by way of the effervescence, fumes, or color changes that occur in the blink of an eye. Often with a sense of nostalgia, colorimetric titrations are remembered by chemistry students because of the vivid color change of the indicator in the solution. The minimal use of chemicals and apparatus in titrations have made them a widely implemented chemistry experiment in high-school and undergraduate curricula around the world.

Depending on the strength of the acid and base being used in the titration, a suitable indicator to indicate the end point is generally chosen so that its color changes in a resulting solution that is slightly acidic, slightly basic, or neutral. Phenolphthalein is a commonly used indicator that changes color over an alkaline pH range of 8.2−10. The appearance of a shade of pink in phenolphthalein-based titration shows the end point of the reaction. A perennial problem that students face with the color change is the difficulty in figuring out which shade of pink is indicative of being close to the end point or which visually represents overshooting the end point. This confusion naturally prompts the students to seek feedback regarding the shade of the pink from an experienced peer, who is often the instructor or the teaching assistant (TA).

In classrooms where the student-to-teacher ratio is high, it is difficult for a teacher to pay individual attention to a student and provide personalized feedback on the experiment. Apart from the primary learning objective of this experiment to teach students about the determination of an unknown concentration using a standardized solution, the experiment holds potential for enabling the students to identify potential sources of error that affect the color change at the end point and ways of resolving those errors. With increasing use of Massive Open Online Courseware (MOOC) programs and homeschooling, there is a need for new research efforts into making independent chemistry learning more seamless for students.

Tackling a problem of this nature requires a solution that can be quickly disseminated among students for use while requiring minimal support from teachers for attainment of the learning outcomes. Recent research efforts in the use of smartphones as

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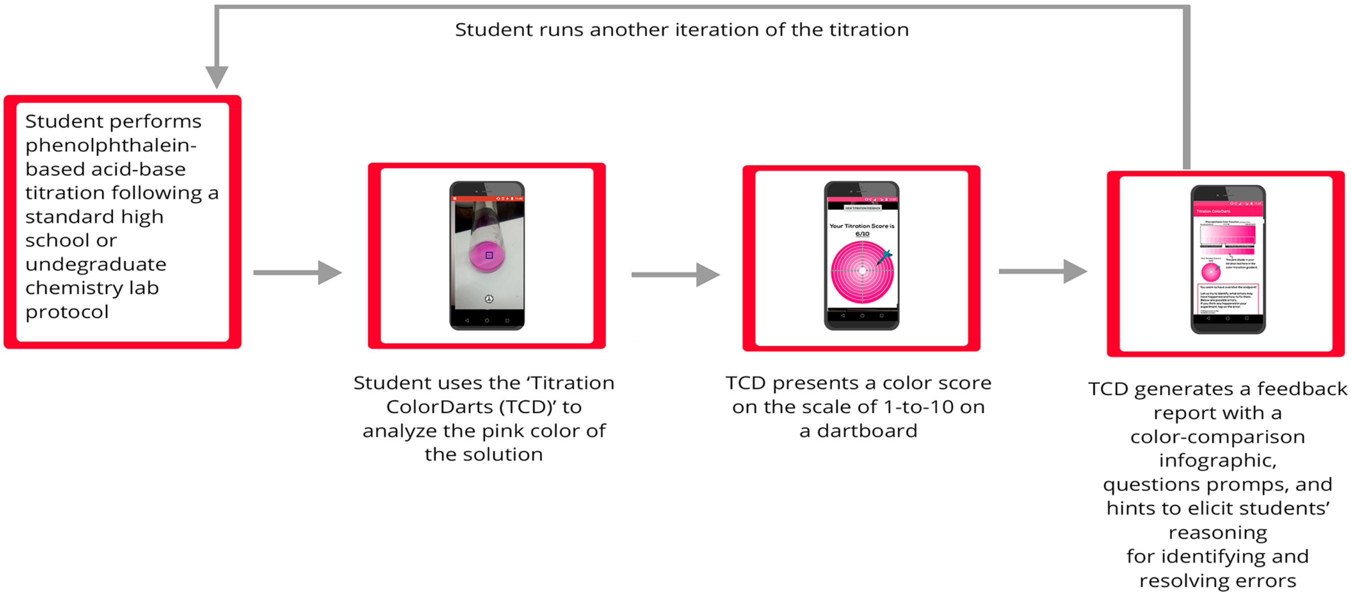

Figure 1. Overview of the Titration ColorDarts assisted experimental flow.

tools have shown promise because smartphones are a reliable platform for devising solutions or apps for a multitude teaching and learning problems faced by teachers and students in chemistry classrooms and laboratories.[1]

Technological implementations in chemistry classrooms,[2−6] more specifically the use of touch-screen-based apps, have demonstrated improved student engagement in classes.[7−9] Mobile-app-based implementations have been extended to the chemistry laboratory for enhancing the learning experience. Studies have reported that devices such as the sensors and cameras of smartphones can be employed effectively in laboratory experiments. Such uses include a method for quantifying gold-nanoparticle concentrations,[10] a method for pH determination,[11] and an augmented-reality colorimetric-titration tool.[12,13]

The literature review is based on the solution components required to address the problem, and we formed a cohesive outline on how smartphones can be used as laboratory tools to enable students to participate in experimental analysis. Drawing from previous studies in which smartphones were utilized (1) as colorimeters for laboratory experiments,[14−16] (2) as a means to conduct assessments,[17,18] and (3) as a way to engage students through games,[19,20] the portable device was found to be a reliable platform for devising an easy-to-use solution.

In this work, the design, development, and implementation of a new smartphone tutor application called Titration ColorDarts (TCD) is discussed. The application uses the camera function and quantifies and analyzes the detected shade of pink to provide performance-related feedback. The feedback includes a gamified color score on a dartboard, a color-comparison infographic, question prompts, and hints for improving the score. The primary objective of the TCD is to enable the students to independently identify the probable errors in their titration experiment and, through self-assessment, take measures to resolve the errors in subsequent experiment iterations. It is vital that novice chemistry students acquire the skill of identifying experimental errors that are part of laboratory measurements in order to gain training as chemists. Moreover, students should be able to determine the effects of the errors on their experiment and eventually learn to resolve the errors, resulting in significant improvement in their recorded data.

STUDENT-LEARNING GOALS

The design and development of TCD was directed by the motivation to enable students to independently be able to

1. identify the optimal end-point pink color that should appear in a phenolphthalein-based acid−base titration and
2. identify potential errors that might have occurred in their experiment and take steps to minimize them in subsequent titration iterations.

SOLUTION DESIGN

Overview of Titration ColorDarts: Pedagogical and Technological Features

The pedagogical design was based on providing performance-related feedback with the motive of enabling students to self-assess their titration experiments. The solution has been implemented through a gamified dartboard color score and a feedback report that includes a color-comparison infographic, question prompts, and hints for identifying errors (see Figure 1).

Delving into the technological design, TCD uses the camera feature of a smartphone to quantify and translate the pink color of a solution into a gamified dartboard performance score and provide a feedback report.

The score is on the scale of 1 to 10. If the solution is a faint-pink color, then the app will display a high score (8−10), indicating that the student has performed the experiment quite well, whereas if the solution is a darker shade, then the score will be low (1−4). Likewise, for intermediate shades of pink, median scores of 5−7 will be displayed.

The generated feedback report shows the student the expected phenolphthalein-titration color along with the color of the solution that they obtained. The report includes question prompts in the form of feedback cards and hints to help learners identify potential sources of error that might have caused the darker shade of pink to appear in the solution. TCD was

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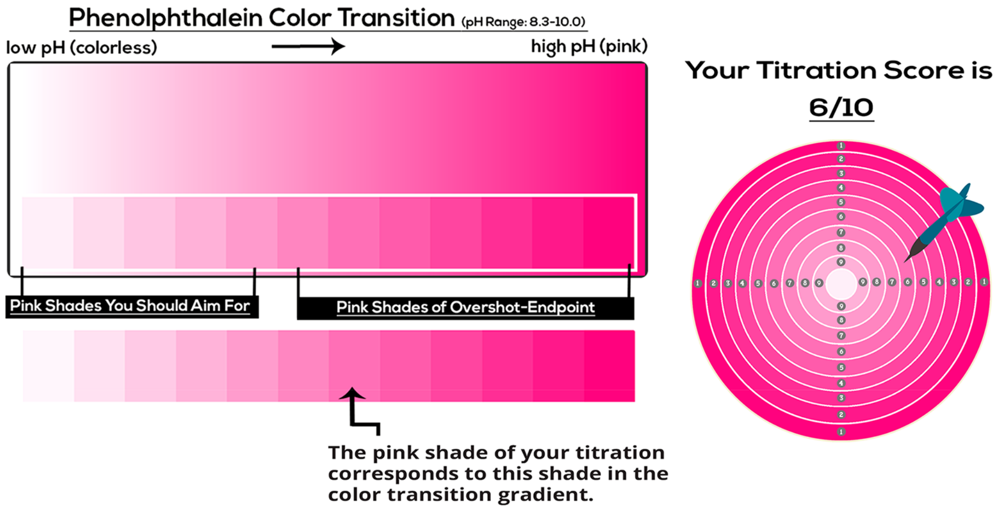

Figure 2. Color-comparison infographic and titration dartboard score.

Figure 3. Screenshots of the navigation and steps for using TCD.

designed to be a companion with a standard phenolphthalein-titration-experiment protocol.

■ PEDAGOGICAL DESIGN

TCD was designed to be able to provide learners with performance-related feedback on their titration-experiment conduct. The feedback is aimed at improving the student's ability to evaluate their performance independently.

Gamified Color-Gradient Dartboard: Feedback on the Pink Shades of the Titration

The primary starting point for designing TCD was to figure out a way to indicate the correctness of a pink color for an expected end point. As observed in typical phenolphthalein-based acid–base titration, the solution color can vary from light pink to dark pink. A TA or an instructor would suggest a student obtain a light-pink shade for an accurate end point, whereas a darker shade of pink would imply an overshot end-point reading. Through such a statement, the lab instructor tries to teach the students that they should be able to deliver a set of precise volumetric-analysis readings that are accurate to a known expected titration-end-point value.

The notions of accuracy and precision, which are associated with the titration-experiment technique, can be related to a dartboard, wherein hitting the bullseye is an indicator of accuracy (getting an expected value), whereas having readings that are clustered together represents precision. Using this analogy, an exploration was done on how the TCD could be

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Table 1. Error Identification and Question Prompts Included in the Feedback Report

Feedback Card	Error Prompt	Question Prompts	Function of Question Prompt: Elaboration	Function of Question Prompt: Reflection
1	I missed the end-point color change.	How observant were you when the solution in the flask turned pink? Do you think you can observe a fainter pink shade than the one you obtained?	Prompting for justifications	
		What do you think you should do in the next titration repetition to observe the color change at the endpoint more clearly?	Elaborating thoughts	
2	I added too much phenolphthalein.	What is likely to occur if you used more or less amount of phenolphthalein than you did for this titration?	Elaborating thoughts	
		What do you think you should take care of while deciding the amount of phenolphthalein required for the titration?		Monitoring and evaluation
3	The drip rate from the buret was high.	How is the drip rate at which you added volumes of titrant (reagent in the burette) to the flask and the appearance of the pink color in the solution related?	Elaborating thoughts	
		What should you do to check the effect of volume of titrant added to the flask and the appearance of the pink color at the endpoint?	Elaborating thoughts	
4	I forgot to rinse and dry the flask.	How did you rinse the flask, the burette, and the pipette before the start of the experiment?		Monitoring and evaluation
		What do you think can possibly contribute as an error in the determination of endpoint if the glass apparatus isn't rinsed?	Elaborating thoughts	

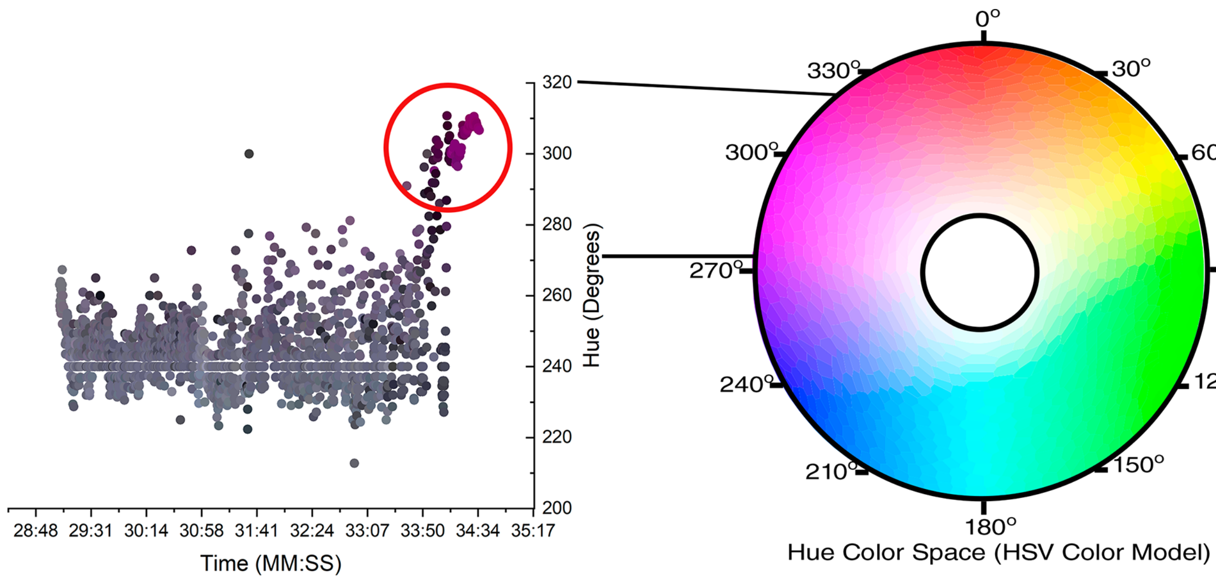

Figure 4. Identification of the hue-value range in the phenolphthalein-titration-color range. The red circle indicates the hue values of a solution turning pink (light to dark).

designed to tell students how close they are to the titration end point.

In the case of phenolphthalein pink, the objective bullseye takes the form of faint pink in the center with the pink getting darker as it goes farther from the center. As the first feedback component to visually showcase how close or far a student's shade of pink is from the desired goal, TCD provides the titration performance as a gamified score (TCD score) on a dartboard (see Figure 2), wherein the bullseye is the desired goal or optimal end-point pink color a learner should aim for. The gradient of pink (light to dark) is mapped to a scoring scale of 10 to 1 (the details are elaborated in the Technological Design section).

Points or scoring is a game-design element that has been used broadly in learning scenarios for positive student outcomes in terms of engagement, participation, and motivation.[21] By scoring the color of the solution, the shade of pink is quantified and presented in a gamified manner for attainment of the student-learning goal of identifying whether the solution color is good enough.

Enabling Students to Independently Assess Their Experiment Conduct with an Error-Feedback Report

The TCD dartboard score, as described earlier, enables students to reason whether their current experimental conduct matches the expected optimum. In order to achieve this optimum, a student must be able to identify the errors in their experiment causing the deviation from expected optimal performance and take steps to resolve them.

In order to provide an error-identification report to a student, the TCD feedback design was based on the "Model of Feedback to Enhance Learning" framework which states that the "main purpose of feedback is to reduce discrepancies between current understandings and performance and the desired goal".[22] The framework provides descriptions of various paths that can help learners bridge the gap between their current and the intended understanding; among the effective methods are those that involve students increasing their efforts to approach more challenging tasks. To reach a particular goal, learners may develop error-detection skills, leading to self-assessment.

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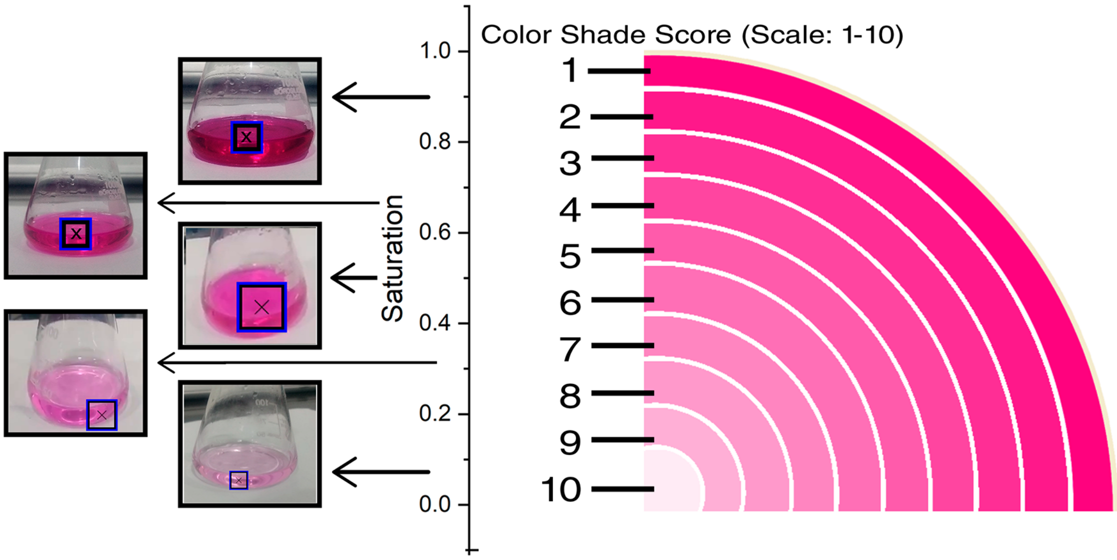

Figure 5. Increasing saturation values as the solution turns darker pink and corresponding score on a scale of 1−10.

As a follow-up, TCD generates a feedback report, which is aimed at the student-learning goal of the identification of experimental errors and the taking of steps to resolve those errors in subsequent iterations.

The report for the student includes a visual comparison of the pink color observed in the solution and the expected or desired faint-pink color along with their TCD score (Figure 3). This is followed by a textual cue that asks students to speculate what specific errors might have happened in their experiment that contributed to the appearance of a darker shade of pink. An interactive checklist is shown regarding the significant errors that the student might have done. The student can click on a particular error and be presented with question prompts. The purpose of presenting students with various question prompts was to scaffold their reasoning in identifying potential sources of error in their experiment and in taking action that minimizes those errors in subsequent experiment iterations.

The prompts were based on the conceptual framework developed for scaffolding ill-structured problem-solving processes using question prompts.[23] The error prompts implemented in the app through feedback cards are categorized on the basis of their type and function, as mentioned in Table 1. It is speculated that the question prompts help students gain a better understanding of their performance in the titration experiment. At the end of each of the prompts, there is an option for a hint, which displays standard instructions that the student should follow to be able to address the error in question. The navigation and implementation of the pedagogical elements in TCD are showcased in Figure 3.

■ TECHNOLOGICAL DESIGN

The programming codes for Titration ColorDarts were written in-house and compiled on the Android Studio platform using the Java programming language. The large market share of Android mobile devices and ease of development were the primary reasons for choosing Android as the base platform.

Detecting and Quantifying the Solution's Pink Shade: Smartphone Colorimetry

Using smartphone's camera feature, TCD converts the red−green−blue (RGB) data of a captured color into the hue−saturation−value (HSV) color model. The reason for using the HSV color model instead of RGB was the ease with which the HSV model exhibits shades of a particular color (in this case, the gradient of pink from light to dark).[24]

For determining the threshold levels of a pink-gradient color change that would be mapped to the corresponding scores on the scale of 1−10, the HSV color data of the color change (colorless to pink) observed in a phenolphthalein-based acid−base titration experiment was recorded. From the recorded data, the hue-versus-time and saturation-versus-time relations were studied, where time is the duration of the experiment. As shown in Figure 4, the graph of hue versus time helped identify the range of hue values that encompassed the pink-color gradient. As shown in Figure 5, looking at saturation values at different instances beyond the end point helped identify the color-intensity-value changes in the experiment indicating the light-to-dark-pink-color shift. Using a combination of both hue and saturation values, the optimal pink color of the end point was determined, and the values of overshot end-point solutions were observed.

The saturation values are on the range of 0−1, where a value near 0 indicates a light color, and a value near 1 indicates a dark color.[24] Using this range, the saturation values of the detected pink color were mapped to the performance scores on a scale of 1−10.

A synopsis of the technique employed to recognize the shade of pink is outlined in the following steps:

1. By pointing the camera function of the app on the flask in which the titration has been performed, the color data at the crosshair mark on the screen is stored (Figure 3, Step 2).
2. The color information is extracted to give RGB values.
3. The RGB data is further converted into HSV color-space coordinates.
4. The threshold parameter, which comprises the hue component of the HSV data, ensures that all shades of pink are covered, and the saturation index detects the variation of shade from light to dark.
5. The conditions mentioned in the above steps are mapped to the scores on the dartboard, evaluating the performance of the experiment. The result is presented to the user through the display of an animated sequence. In the end, a

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color report is generated that provides a visual comparison of the color observed in the titration with an ideal phenolphthalein pink color change.

RESEARCH METHODOLOGY

Participants

For determining the tool's usefulness as a laboratory companion tutor, a two-phase exploratory pilot study was conducted to solicit feedback.

In the first phase of testing, three undergraduate students volunteered to participate in the exercise, who at the time of the study were in years 2−3 of their Bachelor of Science in the Chemical Sciences program. The students were familiar with the hands-on protocol in performing a phenolphthalein-based titration experiment.

In the second phase of testing, undergraduate students (N = 14) who had just begun the first semester of their Bachelor of Science program volunteered to test the application.

In total, 17 students participated in the pilot study.

Procedure

Prior to commencing the exercise, informed consent forms were signed by the students in regard to participation in the study. Each student was provided with a titration-experiment protocol and the glass apparatus used in the experiment (buret, pipet, beaker, and funnel). Among the chemicals provided included a prepared titrant solution of 0.1 N NaOH, the titrand solution of HCl of unknown concentration, the phenolphthalein indicator, and water for rinsing the apparatus.

A walkthrough demonstration on how to use and navigate the TCD application was given to each student before they performed the titration experiment in triplicate. The students were asked to note down their titer volumes, unknown-concentration calculations, and the TCD Score generated from the app.

The students were asked to place the flasks with their pink titration solutions in a fume hood with a white background and diffuse white lighting and then use the TCD's camera function. During the exercise, assistance was only provided to students if they faced any difficulty in navigation of the TCD app.

For the two phases of testing, the TCD was loaded onto two different smartphone devices, a Motorola Z Play and a Redmi 4A, respectively.

Data Sources and Analysis

First Phase of Testing. After completion of the titration exercise, a structured interview was conducted for each participant. The primary goal of the interviews was to understand if TCD was useful in providing students with a mechanism for self-assessment in titration experiments and how effective the various types of feedback were.

The interview included a set of predecided questions that aimed at understanding how TCD helped in conducting the titration experiment.

The questions asked included:

1. What do you think is the difference in performing a titration experiment in the presence of an instructor or a TA and the one you just did using the TCD app?
2. One of the main features of the app is to provide a dartboard score for titration pink color solution, how did this score after completion of each experiment helped you?
3. Another feature of the app is that after the TCD score you get a feedback report with an expected color change, the color you observed, and a few questions and hints. How did the feedback report help you?
4. Can you explain the reasons for the change in your TCD scores between your first, second, or third titration repetition? What do you think are the errors you did in the experiment?
5. How would you like to improve the app?

Students' responses to the interview questions were video-recorded and transcribed. For drawing inferences related to the usefulness of TCD, thematic analysis was used to analyze the interview data.[25]

Second Phase of Testing. Insights from the first phase of testing helped to structure the second phase, in which 14 first-year undergraduate students were participants. After completion of the titration exercise, the participants of this phase were asked to indicate their measure of agreement on a scale of 1 (strongly disagree), 2 (disagree), 3 (neutral), 4 (agree), and 5 (strongly agree) to the following survey statements:

Statement 1: Titration ColorDarts (TCD) App exercise helped me identify the errors in my titration experiment.

Statement 2: By using TCD, I was able to minimize any identified error when I repeated the experiment.

Statement 3: TCD Scores helped me compare the color differences across the titration triplicate.

Statement 4: TCD helped me identify whether the pink color of my titration solution was good enough or not.

Statement 5: I prefer getting feedback on my titration performance from TCD than a teacher or a teaching assistant.

RESULTS AND DISCUSSION

Thematic analysis of the interview data from the first phase of testing gave valuable insights into the usefulness of TCD as a companion tutor for performing titration experiments (Table 2). Themes arising from the interviews with participants showed indications of students self-assessing their experimental conduct, identifying experimental errors, providing reasoning for the results they obtained, and understanding whether the pink color in their solution was good enough.

The results of the survey (summarized in Figure 6) that was part of the second phase of testing (mentioned above) showed salient insights into students' perception regarding the usefulness and integration of TCD into the laboratory activity. Statements 1−4 aimed at understanding whether the application was useful in helping students evaluate their experiments. The responses to these statements were substantially in agreement and asserted the primary objective of TCD in enabling students to assess their titration-experiment conduct independently. Although the majority of students were in agreement with Statement 5, a few mixed responses indicated that the presence of a teacher or instructor is necessary while the experimental procedure is underway.

TCD Limitations and Error Minimization

As observed from the students' use of TCD, a primary limitation of its working was noted in the fluctuation of readings when the lighting in the lab space was not uniform. To check this issue, the students were asked to keep the pink solution flask in a well-lit fume hood and then use the camera function of TCD. For

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Table 2. Thematic Analysis for Identifying the Usefulness of the Titration ColorDarts App

Theme	Representative Student Quotes Exemplifying the Theme
Indicative of formative assessment, that is, feedback that helps the learner identify what the error is, why it is happening, and what they can do to improve. This feedback provides the learner with a way to precisely and continually calibrate and revise their learning.	"A lab instructor or a TA would tell how good or bad my titration was after showing the solution color to them. But, In the app, I was getting scores for my performance, like 7 and 8. "The app is better in a way because as I got a score 7 on 10. I understood that I have to get fainter color next time. I will have to be careful when I repeat the experiment. When I got 8, then I understood that I was close to getting the optimal color. The teacher probably won't be able to tell me this. Performing the titration felt like playing a game and using the app was fun."
Indicative that the TCD Feedback Report helped in identifying potential error sources and helped the students take steps to resolve them when repeating the experiment.	"One thing I understood after completing the entire experiment was that in the first titration I got 3.3 mL as the titre volume, in the second one I got 10.9 mL, and in third the volume was 11.8 mL. The reason I feel for the huge difference in the first two titre values is that I should have rinsed the conical flask before I began the experiment. The first titre value is to be discarded and I didn't use it for calculating the unknown concentration value. I feel this is the answer to the rinsing question in the report. "And regarding amount of phenolphthalein, I tried to drop only one drop each time. Probably for the last (third) titration run, I dropped one drop extra and I think because of that I got a deeper pink shade. Of course, the amount matters. If I add phenolphthalein as little as possible, then I feel I have a better chance of getting a higher score on the app."
Indicative that after noting down the TCD score after completion of each titration repetition, a student was able to compare their performance across the entire experiment concerning reaching an optimal end-point color.	"From first experiment to second repetition, there wasn't much difference. I was trying to have that my solution color to get much lighter. Score of 7 (First TCD Score) to 8 (Second TCD Score) was fine. But when moving on to the final repetition, I was trying to get a fainter pink color, but towards the end I might have added a bit extra drop of base (titrant) which led to a darker pink to appear, hence I got a score of 5, maybe."

proper functioning, it is necessary for the lab to have ambient, diffuse white light.

The TCD is susceptible to returning erroneous results if the ambient light conditions interfere with the camera function of the smartphone. The application's color detection is functional when a pink color is evidently seen. For dilute acid−base (<0.1 N) titrations, the phenolphthalein pink might be close to colorless and challenging to detect correctly. Colors apart from the pink-color gradient of phenolphthalein are not detected by the application. To circumvent and minimize the detection of a wrong shade of pink, lab instructors and students should follow the suggested steps for optimal working of the application:

1. The flask with the pink solution should be placed in a setting with a white background and uniformly diffuse, ambient white light (Figure 7).
2. The flask should be oriented in such a way that there are no reflections from nearby brightly colored objects and no shadows are not falling on it.
3. In order to determine if the light conditions are well-suited for use, a calibration protocol is included in the Supporting Information.

It is assumed that the students will be using their smartphones, and to some extent, the different builds of the devices' cameras could affect color detection.

The instructors' role in executing TCD-assisted phenolphthalein-based titration would be to ensure that students understand the experimental protocol to be followed and how to safely handle the apparatus and chemicals. Because phenolphthalein is active only in the high alkaline pH range, instructors should inform the students that end-point detection by color change does not work with acidic reagents. Presence of a teacher or lab instructor is necessary for helping students test the application for use in a uniform lighting setting. Example of a laboratory activity and a discussion related to redesigning TCD are mentioned in the Supporting Information.

Overall, interview responses, survey results, and students' interactions with Titration ColorDarts indicated that the developed smartphone tutor was useful in helping them identify the optimal titration-end-point pink color and detect errors in their experimental conduct.

■ CONCLUSION

Students often have trouble while performing phenolphthalein-based acid−base titrations in terms of understanding whether the pink shade of the solution is good enough. To address this persisting problem, a smartphone tutor application called Titration ColorDarts (TCD) has been developed and implemented. TCD uses the camera function of the smartphone to quantify the captured pink color of a titration solution, presenting it as a gamified score on a dartboard and providing a feedback report on potential error sources for scaffolding students' reasoning through question prompts and hints. An exploratory pilot study conducted with undergraduate chemistry students indicated that TCD is useful in helping students attain the learning goals of identifying the optimal pink color of a phenolphthalein-based-titration end point and detecting potential experimental errors to be minimized. As a smartphone tool that can easily be accessed and installed, TCD has the potential to be an effective method of helping students who are performing phenolphthalein-based titration experiments independently with minimal support from the instructor.

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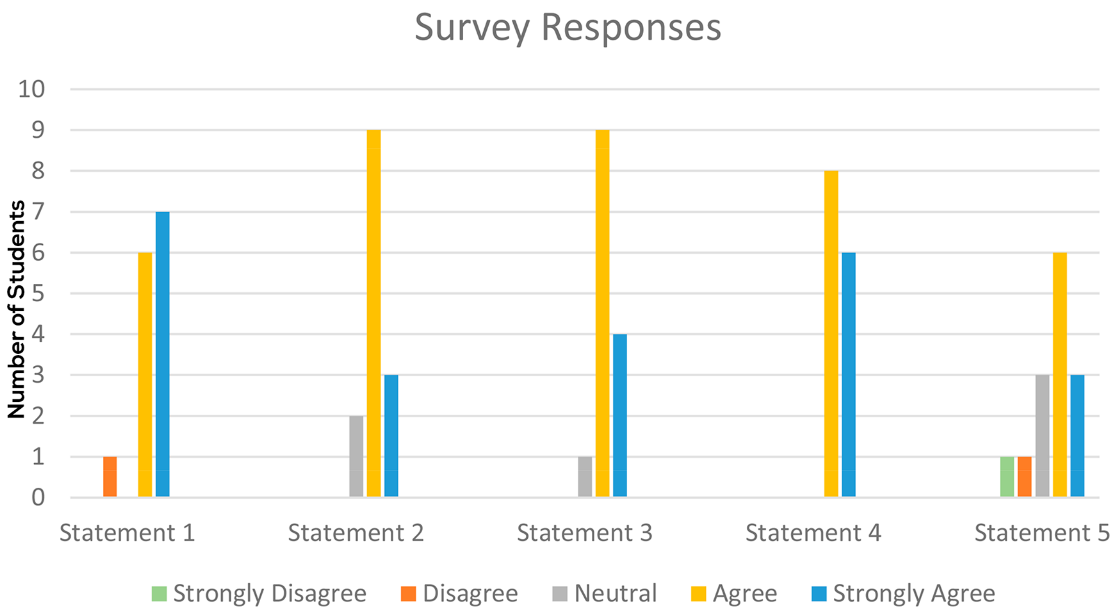

Figure 6. Survey responses from first-year-undergraduate students (N = 14).

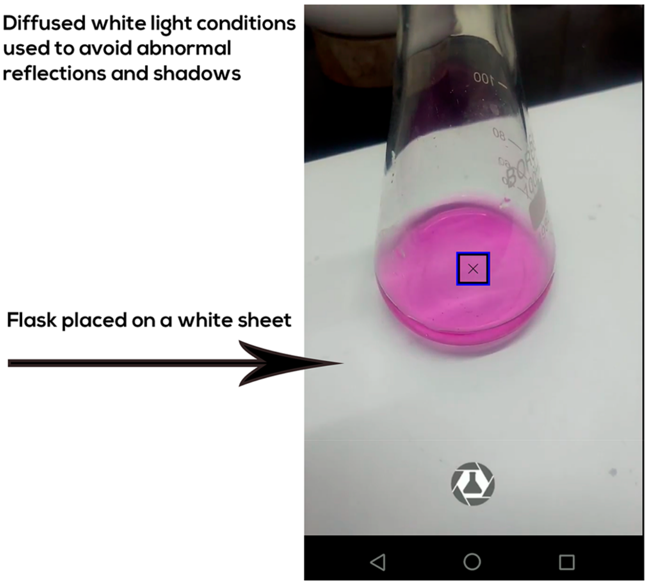

Figure 7. Screenshot of a flask placed against a white background under diffuse-white-light conditions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.8b00708.

Implementation of the Titration ColorDarts (TCD) app as an example of a laboratory activity (PDF, DOCX)
Demo video of the app (MPG)

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Notes

The authors declare no competing financial interest.

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