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Preventing Lab Mistakes: The Importance of Including Rationale in Laboratory Protocols

Caryn Dooner
Western University, cdooner@uwo.ca

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Summary
Experimental rationale is integral to the scientific process. Every step in a scientific protocol is specific and intentional (Hofstein & Lunetta, 1982). In many undergraduate labs there is a "cookie-cutter" approach, where a rigid and simple protocol is given to the students. Often these protocols are lacking rationale, and it can lead students to memorize the steps rather than understand them. Not understanding the rationale behind the protocol can lead to problems when it is time to troubleshoot or alter the experimental parameters. The student's ability to employ critical thinking decreases if they cannot understand the meaning of what they are doing. This workshop aims to communicate the importance of rationale and equip a group of motivated instructors with the resources necessary to emphasize rationale in their laboratory curriculum (Brownell & Tanner, 2012). By the end of the workshop, participants will better understand the need for rationale in scientific protocols. Participants will learn strategies for implementing and assessing the impact of incorporating rationale.

Keywords
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Experimental rationale is integral to the scientific process. Every step in a scientific protocol is specific and intentional (Hofstein & Lunetta, 1982). In many undergraduate labs there is a “cookie-cutter” approach, where a rigid and simple protocol is given to the students. Often these protocols are lacking rationale, and it can lead students to memorize the steps rather than understand them. Not understanding the rationale behind the protocol can lead to problems when it is time to troubleshoot or alter the experimental parameters. The student’s ability to employ critical thinking decreases if they cannot understand the meaning of what they are doing. This workshop aims to communicate the importance of rationale and equip a group of motivated instructors with the resources necessary to emphasize rationale in their laboratory curriculum (Brownell & Tanner, 2012). By the end of the workshop, participants will better understand the need for rationale in scientific protocols. Participants will learn strategies for implementing and assessing the impact of incorporating rationale.

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LEARNING OUCTOMES

By the end of this workshop, participants will be able to:

- Explain why rationale should be an essential element of laboratory protocols in lab-based courses.
- Assess a laboratory protocol, identify rationale-based elements, and incorporate additional rationale as required.
- Take the first steps in assessing the impact of rationale-focused laboratory protocols.

REFERENCE SUMMARIES

Brownell, S. E., & Tanner, K. D. (2012). Barriers to faculty pedagogical change: Lack of training, time, incentives, and… tensions with professional identity? *CBE-Life Sciences Education, 11*(4), 339-346.

Pedagogical change is often difficult to implement. Change is typically led by small numbers of faculty, which at first suggests that the change will be low impact. To increase impact, the small number of interested faculty could involve undergraduate students to increase the breadth of these pedagogical changes. If faculty pursue training to implement pedagogical change on their own, often the institution is not prepared to follow-up and provide support. Typically, faculty gain exposure to teaching during their graduate education. However, teaching is not formally encouraged or incorporated into their identity. For educators looking to facilitate pedagogical change, it is important to be cognizant of these barriers and not be discouraged. To support pedagogical change, there needs to be better incentives as well as early incorporation of teaching into faculty and graduate student identity. Incorporating teaching into graduate education is modelled in this workshop, and this paper speaks to the stage of pedagogical change that the workshop addresses.

Handelsman, J., Ebert-May, D., Beichner, R., & Bruns, P. (2004). Scientific teaching. *Science, 304*(5670), 521.

Scientific inquiry can engage a diverse group of students. Diverse groups of people can bring new perspectives and increase learning opportunities. To capitalize on these learning opportunities, it is important to realize that a typical undergraduate lab does not foster deep scientific understanding. Usually the lab protocols are well-characterized and straightforward. There is no troubleshooting involved, which means that the application of critical thought is not necessary. Engaging students in the scientific process will engage critical thinking, leading to increased retention and understanding. This workshop is designed to provide instructors with an improved means of engaging students in the processes of critical thinking and troubleshooting in an undergraduate laboratory setting.

Hofstein, A., & Lunetta, V. N. (1982). The role of the laboratory in science teaching: Neglected aspects of research. *Review of Educational Research*, *52*(2), 201-217.

The laboratory has an important role in science education. Hands-on experiential learning is especially difficult at larger institutions. The lab provides a scaffold for students to explore the scientific process and engage actively with the material they are taught. The workshop outlined here will hopefully increase the efficacy and broaden the learning outcomes for undergraduate laboratories. Aside from the setting itself, the learning materials that students are provided with are of great importance. A lab manual is typically provided which contains valuable information necessary for the students to complete their work. There is a need for quality lab manuals, which include comprehensive explanations and instructions for students. The lab setting has also been shown to enhance scientific thinking skills, which is important for undergraduate learning.

Hofstein, A., & Lunetta, V. N. (2004). The laboratory in science education: Foundations for the twenty-first century. *Science Education, 88*(1), 28-54.

Lab work and scientific inquiry is a detail-oriented process. Although important, detail can detract from learning and experiencing the conceptual framework that science occurs in. Being given the opportunity to engage in broad and conceptually-driven inquiry allows students to explore their own interests and become self-driven. Metacognitive exercises that encourage students to consider the whole process and manage their learning experience will enhance students' understanding of the lab. When encouraging students to engage in metacognitive exercises, it is important for instructors to willingly engage in dialogue and help students explore the full scope of their scientific inquiry. Engaging in a workshop such as this one will enable instructors to be better prepared for engaging with students in metacognitive exercises.

McFarlane, D. A. (2013). Understanding the challenges of science education in the 21st century: New opportunities for scientific literacy. *International Letters of Social and Humanistic Sciences*, *4*(1), 35-44.

Teaching in any science discipline means that the curriculum is constantly evolving. Although this puts the onus on the instructor to be well-informed and up-to-date, students also need to be invested in their own learning. Explicit teaching, covering all the aspects of a topic, is necessary to allow students to be fully invested in their learning experience. There needs to be emphasis on involved and activity-based learning, such as learning that takes place in a lab setting. Things like diagrams and schematics have been lost due to increasing use of computers. Suggestions to implement an action-oriented approach, one that encourages integration of active learning activities, include: 1) modeling, 2) guided practice, and 3) application. Each aspect involves demonstration, supporting student action, and allowing independent work, respectively. While facilitating those aspects directly in an educational setting, a workshop such as this can bring facilitators and educators together and help improve their ability to effectively educate the next generation of scientists.

CONTENT AND ORGANIZATION

DURATION (MIN)	SUBJECT	ACTIVITY	PURPOSE
10	Welcome and Introduction	Facilitate an ice-breaker (e.g., ask participants to share their favourite lab-based course from undergrad or a favourite recipe).	Help participants to become familiar with each other prior to working together.
10	Introducing the Concept of Rationale	Facilitator/instructor will define what rationale means and why it is important. • Consider using the Miriam-Webster (2016)[1] definition of rationale: "an explanation of controlling principles of opinion, belief, practice, or phenomenon; an underlying reason." Provide examples of how students might make mistakes if they do not understand rationale (e.g., mixing up steps in an experiment). An example of an activity to emphasize the importance of rationale: share a list of materials required to build something (e.g., a wooden chair) but do not share what the final product is supposed to be. • Write the names of tools/materials on post-it notes, and write the function of each tool on the board. • Ask participants to match the post-it notes to board. Then ask participants what they have built (the answer will not be clear). • Explain that connecting the tool to the purpose alone will not always help students identify the desired result.	Identify why "rationale" is essential to supporting students in laboratory settings. Potentially include a game to illustrate to the participants of the workshop how important rationale is to the overall activity or goal one is trying to accomplish.
20	Paired Pairs Activity	Put participants into groups of two (or larger if there is high attendance). The total number of groups must be even so that two groups can pair together part way through the activity. Give each group a card: 1A, 1B, 2A, 2B etc. Card "A" will have a list of ingredients/	This activity is designed to convey how much easier it is to design a coherent protocol when rationale is included.

[1] Rationale (n.d.). In *Merriam-Webster's online dictionary*. Retrieved from https://www.merriam-webster.com/dictionary/rationale.

		utensils. Card "B" will have a list of ingredients/utensils and a rationale for their usefulness. See example activity in Appendix A (Handout 1). Tell participants that they will have 10 minutes to design a coherent set of instructions for the given recipe. Each group must write out the steps in a logical order referring to the ingredients and necessary tools that would lead to the desired product. Next, have the groups pair according to their numbers (Groups 1A + 1B, Groups 2A + 2B, etc.) Ask each paired set to compare the recipes they came up with and discuss the impact of including rationale.	
15	Review of Paired Pairs Activity	Ask groups to share what they learned and how having clear rationale helped with the process. • The groups with the simple list of ingredients/utensils will have had a more challenging time applying logic to creating a recipe protocol than the groups where the rationale was already included. • Relate the recipe instructions to typical laboratory protocols seen in lab-based undergrad courses.	Discuss the impact of rationale on their ability to design a coherent "protocol".
5	Recap	Highlight the importance of including rationale in laboratory settings. Emphasize the need for clarity and simplicity when incorporating rationale. • Protocols can be long and dense for first time users. • Note that decreasing the density of information and highlighting main points - while still incorporating rationale - can be challenging.	Summarize the outcomes of the Paired Pairs Activity.
20	Flowchart Activity	Provide participants with a complete recipe protocol that includes ingredients and rationale. See Appendix B (Handout 2) for an example recipe and worksheet flowchart. • Ask participants to work in their paired-pairs groups (groups of four	Recognize and emphasize rationale in laboratory protocols with the goal of helping students understand the purpose of what they are doing as they go through a lab experiment in class.

		or more). • Have them first identify rationale-based elements in the recipe instructions. • Next, ask them to complete the worksheet flowchart that emphasizes the main points of the protocol, (i.e., the steps that must be understood and mastered for the protocol to be carried out effectively). • After 10 minutes, asks groups to share the main steps they identified and to explain why those steps were key to the process. Emphasize that the same flowchart activity could be used in the design of course-based labs to help students (and instructors) visualize the key steps and associated reasoning.	Solidify the importance of rationale for participants. Participants try out an exercise which they could then transfer to designing pre-lab activities for students.
30	Assessing the Impact of Incorporating Rationale into Laboratory Teaching	Lead a discussion that focuses on what factors are important in assessing whether rationale is already incorporated effectively in a lab-based course. What steps could an instructor take to assess the visibility of rationale in lab protocols? How could rationale be better incorporated? • Record ideas on a whiteboard/chart paper. • Different fields and distinct types of courses may observe differences in rationale implementation. Note: Implementing rationale can include but is not limited to: • Re-writing protocols with a rationale-heavy focus (Hofstein & Lunetta, 1982). • Increasing the number of pre-lab rationale-focused activities (Handelsman et al., 2004). E.g., fill-in-the-blanks, or re-writing portions of the protocol with sub-bullet points including rationale. • Matching rationale to a portion of	Discuss the need for effective rationale implementation and how it may vary across disciplines. (i.e., what works in one course may not work well in others.) Provide a means of formally assessing the impact of incorporating rationale into laboratory teaching to demonstrate its value/impact.

		the protocol (match an explanation to a reagent and its use within the protocol). Ask participants to think about a large-size undergraduate course in their home discipline that includes labs. Discuss how they might they assess the impact of incorporating rationale given the opportunity to implement some of the strategies outlined above. Provide Handout 3 (Appendix C) as a takeaway resource for participants. This handout outlines steps in a research design for formally assessing the impact of incorporating rationale into a large-size, lab-based course. • *Note*: This research would involve approval from the institution's Research Ethics Board, informed consent of students and significant instructor investment.	
10	Conclusion	Highlight the main points from the discussion. Field questions the participants may have regarding implementing rationale or examining efficacy of implementation.	Synthesize the workshop's goals and strategies. Provide an opportunity to ask questions and solidify their knowledge from the workshop.
Total time: 120 minutes			

PRESENTATION STRATEGIES

Facilitators of this workshop should have a good understanding of why rationale is important (Hofstein & Lunetta, 2004) so that they are able to convey key concepts to the participants. This workshop will give motivated individuals the tools to more effectively implement rationale in a lab setting.

The workshop is designed for a minimum of eight participants to a maximum of 40 participants. Active learning through the Paired Pairs and Flowchart activities encourage participants to internalize why rationale is important. Active learning activities also provide a break from the technology-heavy aspect of learning people have become used to (McFarlane, 2013).

Paired Pairs Activity

This activity is designed to convey the importance of rationale and how much easier it is to create a coherent laboratory protocol when complete instructions are available. The goal is to engage participants in groups to develop an understanding of how to implement and communicate rationale. As a facilitator, typically you will have working knowledge of laboratory protocols (or, in the case of this workshop, the recipes) beforehand. Facilitators should remind themselves and their participants to take the mindset of students who are learning the material for the first time when working through the activity.

Flowchart Activity

This activity allows participants to apply their ideas from the Paired Pairs activity to designing new approaches to including rationale in laboratory teaching. By creating a flowchart that emphasizes the main points of a protocol (or recipe), the steps that need to be understood and mastered for the protocol to be completed effectively become clearer. Again, remember protocols/recipes may be familiar to facilitators and participants but someone who is seeing them for the first time (e.g., an undergraduate student) may find them complex and intimidating. Elements of the protocol (such as rationale) will not seem obvious to a "first-time" user.

Assessing the Impact of Incorporating Rationale into Laboratory Teaching

In addition to strategies for implementing rationale into laboratory teaching, participants will also be able to start collecting evidence on the effectiveness of rational implementation. The implementation of rationale has been discussed at length in theory (Handelsman et al., 2004; Hofstein & Lunetta, 1982; Hofstein & Lunetta, 2004; McFarlane, 2013), but at present there is little to no evidence supporting the importance of emphasizing rationale when teaching scientific protocols. As Brownell & Tanner (2012) suggest, finding motivated individuals to initiate teaching research is challenging but one goal of the workshop is to bring like-minded instructors together which may springboard into some collaborative research on teaching and learning.

APPENDIX A

HANDOUT 1 - Paired Pairs Activity – Activity Cards

Example: Recipe for Vanilla Cupcakes

Group 1A	**Ingredients:** - flour, baking powder, baking soda, salt, milk, vegetable oil, vanilla extract, butter, sugar, eggs **Utensils:** - bowl, whisk, measuring cups/spoons, mixer, baking pan, cupcake liners, oven

Group 1B	**Ingredients:** - Flour: thickens batter - Baking powder/soda: helps batter rise - Salt: gives batter flavour - Butter: makes batter light and fluffy - Milk: gives dough strength; adds moisture - Vegetable oil: adds moisture - Eggs: helps batter rise; adds moisture - Vanilla extract: adds flavour - Sugar: sweetens batter **Utensils:** - Bowl: allows ingredients to be mixed together - Whisk: blends ingredients and incorporates air - Measuring cups/spoons: precise addition of various ingredients - Mixer: allows aeration and facilitates mixing - Pan: limits the size of each cupcake - Cupcake liners: prevents cupcakes from sticking to the pan - Oven: applies heat to stimulate baking

Note to facilitator: The recipe (a.k.a. "the answer key") can be found at the following link:

Tack, K. (2008, April). Vanilla cupcakes. *Martha Stewart Living*. Retrieved from http://www.marthastewart.com/254593/vanilla-cupcakes.

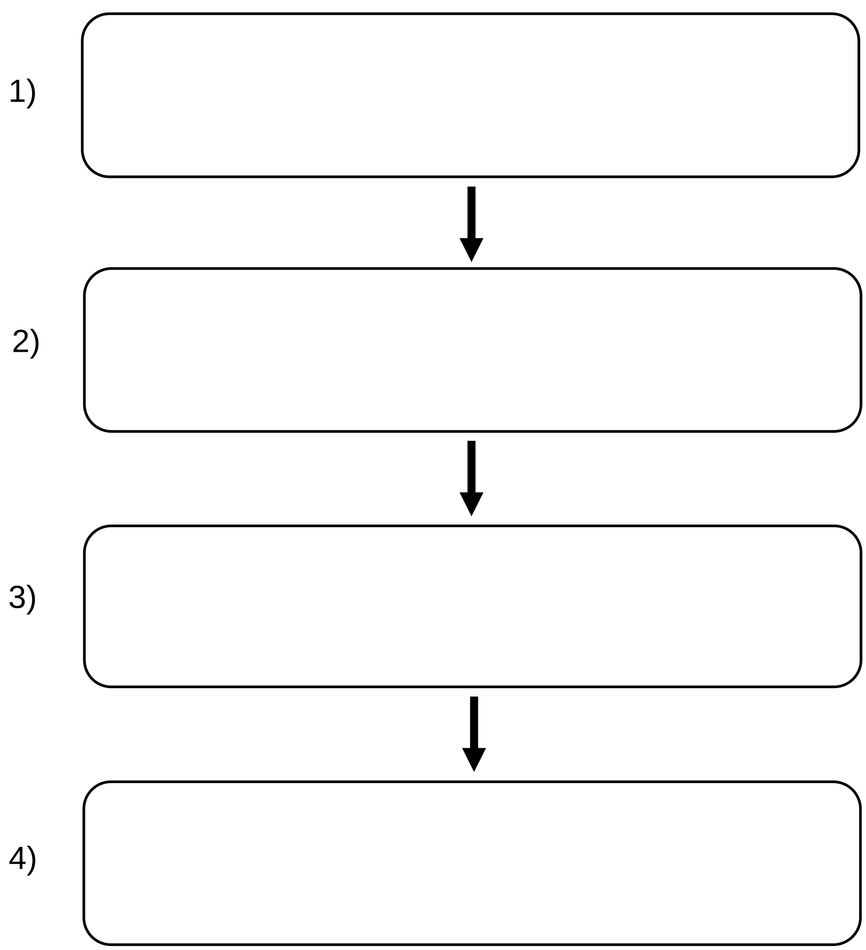
APPENDIX B

HANDOUT 2 - Flowchart Activity – Activity Worksheet

Example: Recipe for Hollandaise Sauce

Ingredients: 4 large eggs, 250 g unsalted butter, ¼ lemon

In a gently heated heavy-based pan, whisk the following ingredients together continuously: egg yolks, butter, and two tablespoons of water. Thorough mixing is key in giving the mixture a good consistency. The sauce will thicken as the butter melts; ensure that the sides of the pan are cool to the touch at all times and do not increase the heat. Over-heating can result in burning, making the mixture unusable. Do not leave the mixture unattended. You may turn the heat up to medium-low and whisk vigorously until the sauce thickens only AFTER the butter has melted. If the mixture begins to steam do NOT cease whisking but you may remove the pan from the heat source. Again, mixing is important in maintaining good consistency. Once the sauce has thickened to the desired consistency, you may add the final two ingredients. Stir in one tablespoon of lemon juice and any other seasoning you would like, to taste. Adjust if necessary. The sauce does not reheat well, so serve immediately or store in warm place/vacuum flask until needed.



Flowchart Activity – Answer Key for Facilitators

Bolded type indicates elements of rationale, and can be incorporated between bubbles on the flow chart (where the arrows are).

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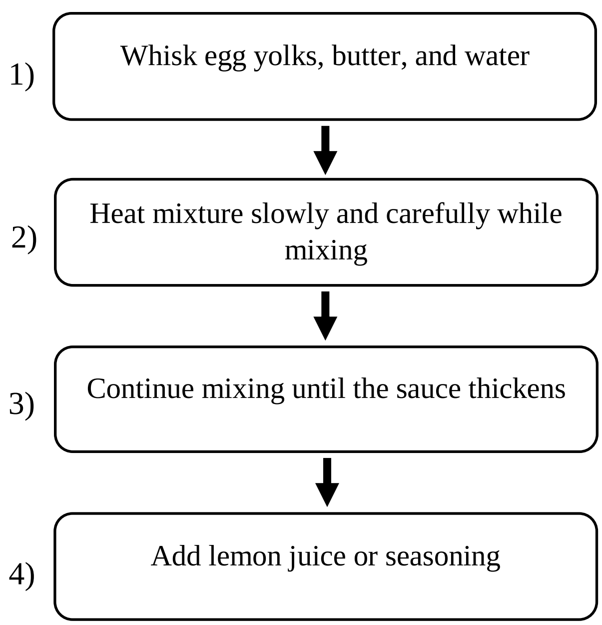

This recipe was modified from:

Cloake, F. (2011, May 5). How to make perfect hollandaise sauce. *The Guardian*. Retrieved from https://www.theguardian.com/lifeandstyle/wordofmouth/2011/may/05/make-perfect-hollandaise-sauce

APPENDIX C

HANDOUT 3 - Assessing the Impact of a Rationale Focus in Laboratory Teaching

The following is an example study design for examining the impact of implementing a rationale focus into a laboratory-based undergraduate course.

Prerequisites

- Large class size (i.e., 200+ students; minimum four lab sections)
- Labs run weekly or semi-regularly throughout the course
- Research Ethics Board approval, departmental support, and informed student consent.

Context

Take, for example, a large-sized, second year biology course with multiple sections and weekly labs. A rationale-heavy focus could be introduced to this course by revising protocols in the current lab manual.

Figure 1 outlines how 24 lab sections could be divided into four groups. Modes 1 and 2 are control groups that will have consistent methods of rationale implementation throughout the course. Modes 3 and 4 are treatment groups that will have the method of rationale implementation swap part way through the course. Alternatively, if the study were run across two terms, the first group of students could serve as the Mode 1 control group, while the students in the second term could be divided into the three remaining groups (Modes 2-4).

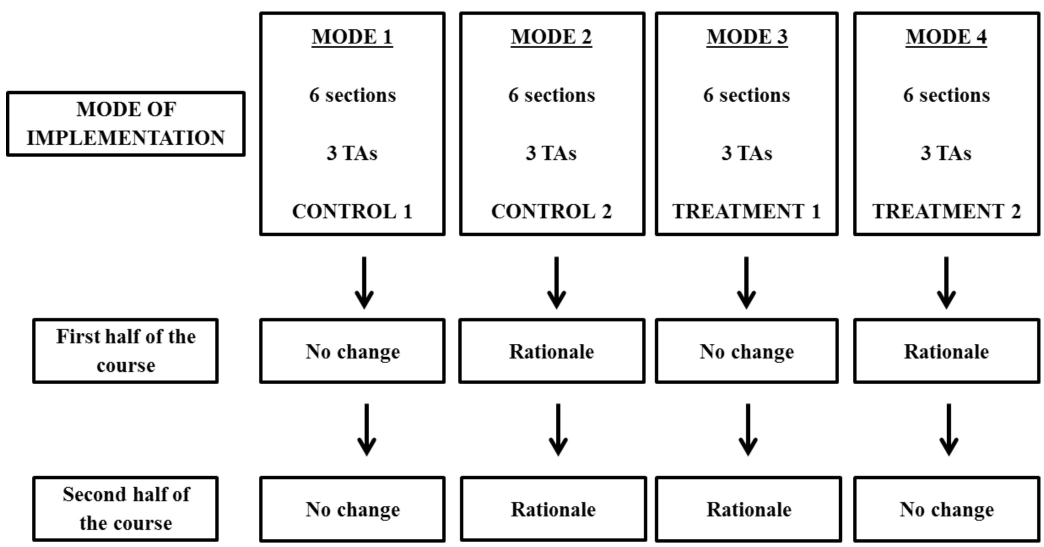

Figure 1. Possible control and treatment design for assessing the impact of rationale-focused labs.

Five mechanisms of analysis could be consistently applied to all lab sections to assess the impact of incorporating a rationale-heavy focus into the course.

1. **Self-identification of errors**. Assess whether or not students can identify the parts of the experiment that went wrong or were performed incorrectly due to errors in carrying out the protocol.
    - An accurate account of any issues that arose during the lab will be required, and a subsequent analysis by the student of whether or not these affected the outcomes or results of the experiment.

2. **Consistency between self-identification and result accuracy**. If a student self-identifies no errors, but their results are inaccurate, it is likely that the student may not have noticed an error that occurred in the lab. Note any inconsistencies in reporting (mismatch between identification of errors and accuracy of results). Also consider having Teaching Assistants record any obvious mistakes they observed.

3. **Exam questions**. Some exam questions typically pertain to labs; thus it would be possible to include questions relating to rationale on an exam. By examining the correlation between responses and modes of rationale, implementation would allow for a quantitative analysis of how the mode affects student understanding of lab protocol.

4. **Grades**. Comparing grades across modes would assess the potential correlation between rationale implementation and student learning.

5. **Self-confidence in understanding**. Consider using course evaluations to quantify how confident students are in their understanding of scientific rationale as it pertains to the course. Assess each mode for a correlation with perceived higher self-confidence.