

HOW WE TEACH | *Generalizable Education Research*

Using whiteboards to support college students' learning of complex physiological concepts

Caron Y. Inouye,¹ Christine L. Bae,² and Kathryn N. Hayes³

¹Department of Biological Sciences, California State University, East Bay, Hayward, California; ²Department of Foundations of Education, Virginia Commonwealth University, Richmond, Virginia; and ³Department of Educational Leadership, California State University, East Bay, Hayward, California

Submitted 23 December 2016; accepted in final form 19 July 2017

Inouye CY, Bae CL, Hayes KN. Using whiteboards to support college students' learning of complex physiological concepts. *Adv Physiol Educ* 41: 478–484, 2017; doi:10.1152/advan.00202.2016.—Research underscores the importance of retrieval-based practice and application of knowledge for meaningful learning. However, the didactic lecture format continues to persist in traditional university physiology courses. A strategy called whiteboarding, where students use handheld dry erase boards and work in small groups to actively retrieve, discuss, and apply concepts presented in the lecture, has the potential to address challenges associated with actively engaging students in science courses for greater learning. The purpose of this study was to empirically examine the potential benefits of whiteboarding for increasing students' understanding of animal physiology concepts. Student performance on physiology questions assessing concepts taught using lecture only vs. concepts taught using lecture and whiteboarding were compared within the term that whiteboarding was used, as well as across whiteboard and lecture-only terms taught by the same instructor. Results showed that when whiteboarding was incorporated in the course, student performance on items that assessed concepts corresponding to the whiteboarding activities were significantly higher compared with performance on items that assessed concepts taught through lecture only. These patterns in student performance were found within and across terms. Taken together, findings point to whiteboarding as an effective tool that can be integrated in traditional lecture courses to promote students' understanding of physiology.

whiteboarding; physiology education; active learning; retrieval strategy

DEEP UNDERSTANDING of animal physiology requires complex reasoning, such as mapping the sequence of events in physiological systems and predicting the consequences of homeostatic imbalance. An important goal for physiology educators is to create learning opportunities for students to go beyond rote memorization of terms and processes, and toward developing sophisticated mental models of physiological phenomena. Unfortunately, physiology college courses are often taught entirely in lecture formats, in which students have little to no in-class opportunities for actively engaging with the material presented by the instructor. Despite the recognition of the importance of retrieval strategies and active learning (3, 6, 23),

research on the classroom-based strategies that engage such processes in higher education science classrooms remains scarce. Research in this area is important, particularly as university science educators are increasingly seeking alternative (nonlecture) pedagogies that will provide students with active learning experiences toward deeper understanding of course content.

In this study, we test whiteboarding as a retrieval-based learning strategy that instructors can embed in their lectures to engage students in active recall of target information and collaborative problem-solving (7). Whiteboarding is a pedagogical tool for addressing the challenges instructors of large science courses face in creating opportunities for students to meaningfully engage with and apply content presented in the lectures. Briefly described, students are provided with handheld erasable whiteboards and dry erase markers at the beginning of the class, and throughout the lecture, the instructor presents open-ended prompts based on the content covered. Students then work in small groups to retrieve, discuss, and apply target physiology concepts presented in the lecture. Although whiteboards are commonly used in primary and secondary classrooms, its presence in university courses remains elusive (16). Further, there is a dearth of studies that have empirically examined the effectiveness of whiteboarding for student learning (16).

Additionally, there is a lack of theoretical frameworks to explain the mechanisms engaged during whiteboarding activities that may support deeper learning. Research in the cognitive sciences can shed light on possible explanatory mechanisms. In particular, research examining learning strategies in higher education underscores the powerful role of active retrieval, or actively accessing stored knowledge, from memory on learning (5, 6, 21, 23). This phenomenon has been dubbed the “testing effect” or “retrieval-based learning,” challenging the traditional view that retrieval is a neutral process that occurs only after the material has been learned (13, 20). Rather, scholars in this field argue that repeated and active retrieval of information supports long-term retention (9, 13, 20). To date, studies have largely examined the effect of retrieval practice in controlled laboratory settings, consistently showing that students in the active retrieval condition demonstrate superior retention of learned material (e.g., information from an expository text) compared with students in alternative learning conditions, such as rereading text (5, 13, 20). Explanations offered for the improved information retention documented across

Address for reprint requests and other correspondence: C. Inouye, Dept. of Biological Sciences, California State University, East Bay, 25800 Carlos Bee Blvd., Hayward, CA 94542-3090 (e-mail: caron.inouye@csueastbay.edu).

studies chiefly propose that applying the retrieval strategy during study requires more cognitive effort, and this added mental effort supports processes optimal for learning. For example, it has been suggested that increased mental effort in retrieval practice leads to elaborative processing (e.g., integrating new information with prior knowledge) (4) and stronger memory traces, increasing students' ability to remember and use information stored in long-term memory (24). While research that supports the importance of retrieval for learning is growing (8, 15, 20), the translation of findings from controlled laboratory studies to classroom-based applications in science education is still nascent. Additionally, with the exception of a few recent studies, the assessment tasks used in the previous research do not reflect the deep understanding of complex scientific concepts required in university science courses.

In addition to engaging students in active retrieval, whiteboarding aligns with social constructivist approaches to instruction by creating opportunities for students to co-construct understanding of science ideas through peer-to-peer discussions (10, 16). Several studies demonstrate the positive role of peer discussions on college students' mastery of science concepts, showing that even naive group discussions are beneficial for deeper understanding compared with not participating in discussion at all (8, 9). Particularly in physiology courses, where students are asked to grapple with complex problems that require understanding of systems in constant interaction (e.g., the interaction between the cardiovascular, excretory, and nervous systems in regulating cardiac output), whiteboarding can be used to support students in collaboratively making sense of challenging scientific concepts. For example, as students work together on a whiteboard prompt, they co-develop a complete problem representation that identifies core features of the task (e.g., when asked to explain why given factors like increased stroke volume and vasoconstriction increase mean arterial pressure, students may start by writing down an essential set of mathematical expressions that clearly lay out key relationships). This problem definition stage is a critical precursor to successfully completing subsequent problem-solving steps, particularly for the multifaceted types of problems common in advanced physiology courses (1, 18). Whiteboard activities also create a fluid workspace that enculturate students into particular ways of knowing and representing the world in science, as they pose questions, informally share ideas drawn from prior knowledge, and negotiate discrepant understandings. This way of promoting student-driven scientific discourse supports the development of epistemic frameworks and social networks that mirror how knowledge is communicated, represented, and developed in a scientific community (10, 12, 14).

Finally, the whiteboarding activities provide valuable instructional opportunities for instructors to scaffold students' learning and formatively address common student misconceptions (16). For instance, instructors can intentionally select concepts that they have found difficult to teach and/or that students consistently demonstrate difficulty in understanding and use the whiteboarding activities to cover these concepts in more depth. Instructors can also design whiteboarding prompts to target the types of knowledge and skills students will be expected to demonstrate on course assessments. Here, whiteboarding can serve to support students in developing fluency

with the processes required to be successful on summative assessments by providing in-class practice on complex problem-solving items that mirror the types of items present on exams (9). Finally, incorporating whiteboarding in lectures provides instructors with multiple points of entry into their students' thinking, allowing them to formatively monitor their students' level of comprehension throughout the course. For instance, as student groups share their whiteboard responses in small groups and during the whole-class discussions, instructors have an opportunity to address potential gaps in understanding in real time.

As an illustration, a whiteboard prompt in this study required students to "Show Fick's law of diffusion. Explain what this equation is telling you in the context of factors affecting diffusion rates." In this exercise, students had to deconstruct and identify the key components of the problem (information needed to answer the question in the context), negotiate ideas regarding factors that influence diffusion rates, and retrieve key factual information (i.e., the equation for the net rate of diffusion). With fellow classmates, they then needed to retrieve and apply a mathematical expression to explain a science phenomenon (i.e., how the variables represented in the equation influence the speed at which substances diffuse across cell membranes and how these factors might optimize diffusion of certain substances across the membrane). Furthermore, an instructor-facilitated class discussion following the whiteboarding exercise served to clarify and deepen students' understanding of target content ideas, by identifying and resolving common misconceptions or discrepancies in students' responses. Taken together, the use of whiteboards in university science courses has potential to engage students in several critical processes for deeper learning. Students are given the opportunity to actively retrieve, rather than passively encode (e.g., reading and/or writing notes) scientific ideas, vocabulary, and principles from the lecture to promote long-term retention of that information. Additionally, students actively co-construct deeper understanding of the science concepts by applying information from the lecture as they critically problem solve, reflect on, and clarify their diverse understandings of target science ideas with their peers and instructor.

The main purpose of this study was to examine whether incorporating whiteboards in a traditionally lecture-based physiology course increased students' understanding of physiology concepts. To this end, we first compared student performance on open-ended physiology items assessing concepts taught using lecture only (Lecture-Only), to the same student performance on items that assessed concepts taught using lecture coupled with in-class whiteboarding activities [Lecture + Whiteboard (WB)] in the 2015 term. Additionally, we compared student performance on the Lecture-Only vs. the Lecture + WB items in the 2015 term to two previous terms (2011, 2012) in which the course was taught by the same instructor using a traditional lecture-based format. We hypothesized that students in the 2015 term (Lecture + WB) would demonstrate greater performance on the Lecture + WB items compared with the Lecture-Only items. We also hypothesized that students in the 2015 term would outperform students in the 2011 and 2012 terms (Lecture-Only) on the Lecture + WB items.

Table 1. Demographic information from 2011, 2012, and 2015 terms of students enrolled in the advanced animal physiology course

Category	2011	2012	2015
<i>n</i>	78	63	49
Sex, %			
Male	23.08	37.14	36.84
Female	76.92	62.86	63.16
Ethnicity, %			
Caucasian	14.10	10.00	10.53
African American	1.28	1.43	7.02
Hispanic/Latino	17.95	15.71	22.81
Asian/Pacific Islander	53.85	60.00	52.63
Native American/Alaskan native	1.28	2.86	0.00
Other	11.54	10.00	7.02
First-generation college students, %	23.08	32.86	52.63
Pell Grant eligible, %	32.05	40.00	49.12

n, No. of students. Pell federal grant eligibility is an indicator of socioeconomic status, available only to low-income students.

METHODS

Participants

This present study examines the effectiveness of whiteboarding in an upper division animal physiology course at a university in the western region of the United States, which serves a high percentage of students from underrepresented populations (see Table 1 for sample demographic information). University Institutional Review Board approval was obtained. The 10-wk course was taught by the same instructor in the 2011 ($n = 78$), 2012 ($n = 63$), and 2015 ($n = 49$) terms. Over 90% (e.g., 91.5% in Winter 2015, 93.6% in Fall 2011) of

students enrolled each term were majors in biology, as this was an upper division course required for biology majors (with corresponding prerequisites). In some cases, students in other majors (e.g., biochemistry, kinesiology, health sciences) were also enrolled. However, students in this course were all from a natural science major. In the 2011 and 2012 terms, the instructor taught the course using a traditional lecture-based format, whereas, in 2015, the instructor incorporated whiteboarding one to three times per class based on preselected topics. χ^2 tests of independence were performed to examine whether groups (or terms) were comparable with regard to sex or ethnicity. Results showed that no significant differences existed among the three terms by sex [$\chi^2 = (2, 190) = 4.33, P = 0.12$] or ethnicity [$\chi^2 = (14, 190) = 12.43, P = 0.57$]. This provides evidence for the equivalency of student backgrounds by sex and ethnicity across the three terms.

Whiteboarding

In the 2015 term, the instructor introduced whiteboarding in an advanced animal physiology course. The instructor provided students with erasable handheld whiteboards, black dry erase markers, and paper towels (stored on a cart to transport between the office and the classroom). The instructor presented approximately two to four open-ended prompts strategically during the lecture to bolster and probe students' understanding of specific content. The whiteboarding activities, broadly categorized, included concept mapping, interpreting a diagram, using a mathematical formula to calculate a value, mapping a sequence of events, and/or writing explanations using a diagram (see Table 2 for examples). In pairs or small groups (~2–4 students), students discussed the prompt and then documented their responses on the whiteboards through writing, formulas, and/or diagrams. As students engaged in the whiteboarding activities, the instructor walked around the classroom to provide feedback, answer questions, and/or redirect misconceptions. Students were also encouraged to discuss

Table 2. Examples of whiteboard prompts by general topic and type of activity during the 2015 term

Type of Whiteboarding Activity	General Topic	Whiteboard Prompt
Concept mapping	Cardiovascular physiology	Construct your own concept map of cardiac output. Include all of the terms listed (e.g., stroke volume, heart rate, EDV, ESV, venous return). Arrows between terms should be accompanied by the appropriate connecting terms listed (e.g., decreases, increases, directly affects, inversely affects).
Interpreting a diagram	Neuronal physiology	Diagram of unmyelinated vs. myelinated axons from Giuliodori MJ, DiCarlo SE. <i>Adv Physiol Educ</i> 28: 80–81, 2004 (12a). This diagram shows me that _____.
	Osmoregulation	An inaccurate diagram of a nasal salt gland cellular mechanism is shown. Based on what I told you regarding the supraorbital salt gland in seabirds, provide a more accurate and well-labeled drawing of how Na^+ , K^+ , and Cl^- are drawn into the secretory cells from the blood and then moved out of the secretory cells into the lumen of the salt gland tubule.
Using a mathematical formula	Energetics/metabolism	A cat has a body mass that is ~100× greater than a mouse, yet its metabolic rate is not 100× greater than a mouse's. Apply Kleiber's law to show how you would calculate how many times greater the cat's metabolic rate is compared with the mouse's.
Mapping the sequence of events	Renal physiology	Create a diagram or describe (with key terms underlined) the route of blood flow through the kidneys, starting with blood entering the kidneys and ending with blood leaving the kidneys.
	Digestive physiology	Using a well-labeled diagram, show/explain how glucose is moved from the lumen of the small intestine into the bloodstream.
Verbal explanation with a diagram	Sensory mechanisms	You smell a fragrance that "brings back" happy childhood memories of blowing bubbles. Draw a diagram of and clearly label the sensory projection pathway from the binding of the odorant molecule to the route action potentials take to the specific part of the brain that elicits the output of "emotional memory."
	Muscle physiology	Draw and clearly label three distinct motor units in one muscle (made up of multiple muscle fibers). If the three motor units have threshold potentials of 1, 2, and 3 mV, respectively, then what stimulus strength would result in the strongest contraction of the whole muscle? Explain why.
	Respiratory physiology	Diagram and explain how the mammalian lung acts as a negative pressure pump through an entire respiratory cycle. Your explanation must include at least the following terms: Boyle's law, P_{atm} , P_{alv} , pressure gradient, inhalation, and diaphragm.

EDV, end-diastolic volume; ESV, end-systolic volume; P_{atm} , atmospheric pressure; P_{alv} , alveolar pressure.

their ideas and help one another across groups, as well as to take a photograph of their whiteboard answers as a reference at the end of the activity. Each whiteboarding activity lasted 5–15 min. Students' responses were then displayed by holding up their whiteboards, and one to two groups were selected to present their answers. The instructor provided small-group and whole class feedback on the responses (e.g., addressing misconceptions) and facilitated class discussion (e.g., pointing out discrepant ideas for students to further explore).

Research Design

Within-subjects design. First, a within-subjects design compared one class' (2015 term) scores on items that assessed concepts related to the topics of the in-class whiteboard activities compared with items that were taught using lecture only. Students were asked a series of open-ended, short-answer questions in each of the three summative assessments administered throughout the term. These questions assessed course learning outcomes related to the content in animal physiology (e.g., predicting the physiological consequences of homeostatic imbalance) and the application of disciplinary science practices (e.g., demonstrating the ability to use data to explain physiological phenomena). Two scores were calculated for this study: 1) the Lecture-Only score that represents the percentage correct on items that measured understanding of concepts taught using Lecture-Only; and 2) the Lecture + WB score that represents the percentage correct on items that measured understanding of concepts that were taught using both lecture and whiteboarding.

Between-subjects design. Second, a between-subjects design compared student scores from the 2015 term to student scores on the same items from two previous terms (2011 and 2012) that were taught using Lecture-Only.¹ This comparison accounted for the possible confounding effect of item difficulty driving performance differences between the Lecture + WB items and the Lecture-Only items when examining student performance in the 2015 term. Specifically, if the Lecture + WB items are lower in difficulty compared with the Lecture-only items, we would expect students in the 2011 and 2012 terms to also demonstrate significantly higher performance on the Lecture + WB items, despite having been taught all of the concepts through a traditional lecture format. However, if performance differences between the Lecture + WB and the Lecture-only items are only found in the 2015 term (when whiteboarding was introduced), we can more confidently conclude that the use of whiteboards (rather than test difficulty) is driving the difference in student performance. Thus the between-subjects comparison across the three terms serves to rule out the possible confounding factor of difficulty level driving performance differences between the Lecture + WB vs. the Lecture-Only scores. The comparison of student performance across the three terms was also conducted using disaggregated scores representing a specific type of whiteboarding activity (detailed below), as well as students' end-of-course grades.

Summative assessment. The animal physiology summative assessments consisted of four to six short-answer questions that were administered three times throughout the 10-wk course, across all 3 yr. Each exam was noncumulative and assessed a specified range of topics covered in the weeks preceding the exam. The first exam assessed topics related to membrane physiology, neuronal physiology, and the vertebrate nervous system. The second exam focused on sensory physiology, muscle physiology, and cardiovascular physiology. The third exam focused on respiratory physiology, excretion, osmoregulation, digestion, metabolism, and thermal physiology. The

short-answer items were worth three to seven points each, and all items were scored by the instructor using a standardized scoring rubric. For example, on a 4-point question asking how the mammalian lung acts as a negative pressure pump, students were given 1 point for providing the equation for Boyle's law (to show the inverse relationship between pressure and volume); 1.5 points for describing what occurs during inhalation [0.5 each for mentioning that 1) respiratory muscles contract which increases thoracic cavity and lung volume, thereby causing 2) a drop in alveolar pressure (P_{alv}) below that of atmospheric pressure (P_{atm}) (so, $P_{alv} < P_{atm}$), thereby causing 3) air to move into lungs down the negative pressure gradient]; and 1.5 points for describing what occurs during exhalation (relaxation of respiratory muscles to reduce lung volume, increase in intrapulmonary pressure above P_{atm} ($P_{atm} < P_{alv}$), causing air to move out of the lungs down the negative pressure gradient). Reported are the mean scores on the Lecture-Only and the Lecture + WB items that represent the percentage correct.

Analyses. To compare student performance on the Lecture-Only to the Lecture + WB scores, mean scores on open-ended short-answer items were computed. Scores are expressed as means \pm SE of the mean. To test our first hypothesis, within-subjects paired *t*-tests were conducted to examine if there were significant differences between the Lecture-Only and the Lecture + WB scores among students in the 2015 term. To test our second hypothesis, ANOVAs were conducted to examine whether there were significant differences in the Lecture-Only vs. the Lecture + WB scores by term, two of which were taught using lecture only (2011, 2012) and one that was taught using whiteboards in addition to lecture (2015).

Additionally, ANOVAs were conducted to compare performance on exam items categorized into one of five possible types of whiteboarding activities (concept mapping, interpreting a diagram, using a mathematical formula, mapping the sequence of events, or explanations using a diagram) across the three terms to more closely explore whether the type of whiteboarding activity has an effect on student performance. Finally, an ANOVA was conducted to compare the three groups in regards to final course letter grades. Where an overall omnibus *F*-test was significant, pairwise comparisons using Tukey post hoc multiple-comparison tests were conducted. Effect sizes are reported using Cohen's *d* and partial η^2 (η_p^2) for the *t*-test and ANOVAs, respectively. SPSS (version 24, IBM, Armonk, NY) was used to conduct statistical analyses. Statistical significance for all tests was set at $P < 0.05$.

RESULTS

In support of the first hypothesis, in the 2015 term, students performed significantly better on the Lecture + WB questions (means \pm SE = 66.52 \pm 0.03) compared with the Lecture-Only questions (means \pm SE = 54.14 \pm 0.03; $t_{48} = 6.51$, $P < 0.001$, $d = 0.58$). Supporting the second hypothesis, results showed that students in the 2015 term significantly outperformed students in 2011 (means \pm SE = 52.02 \pm 0.02, $P < 0.001$) and 2012 (means \pm SE = 55.43 \pm 0.02, $P < 0.01$) terms on the Lecture + WB items ($F_{2,187} = 9.58$, $P < 0.001$, $\eta_p^2 = 0.09$). The pairwise difference in student performance on the Lecture + WB items between the 2011 and 2012 terms was not significant ($P = 0.52$). Furthermore, results from the comparison of performance on the Lecture-Only items showed that there were no significant differences across the 2011 (means \pm SE = 55.26 \pm 0.03), 2012 (means \pm SE = 54.07 \pm 0.02), or 2015 terms ($F_{2,187} = 0.079$, $P = 0.92$, $\eta_p^2 = 0.001$) (Fig. 1).

Finally, descriptive statistics of student performance across the three terms by whiteboarding activity type showed that performance on assessment items that aligned with white-

¹ Across all three terms (2011, 2012, 2015), the instructor also incorporated short activities, such as iClicker questions, exit tickets, and paper-and-pencil prompts. However, lecture was the primary approach to teaching concepts in the 2011 and 2012 terms, whereas the whiteboarding activities, unique to the 2015 term, were a substantial addition to the lecture.

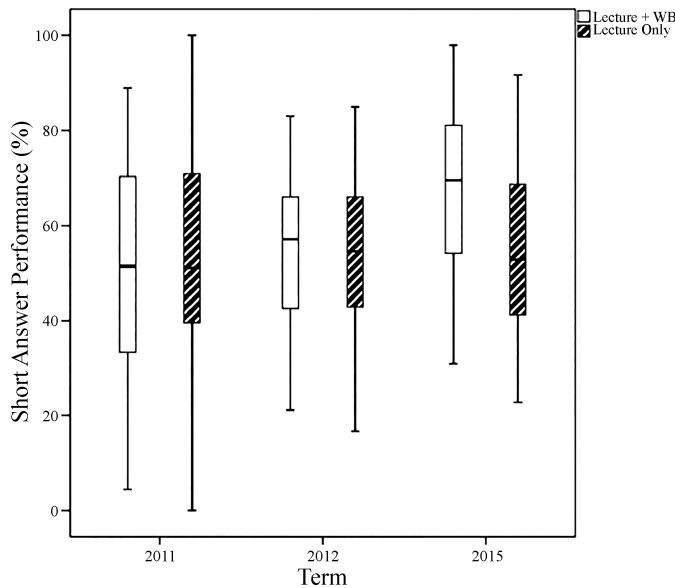


Fig. 1. Box-and-whisker plots to compare the mean percentage of correct responses for students in the 2011, 2012, and 2015 terms on Lecture + WB and the Lecture-Only short-answer items. Box represents the 25th and 75th percentile, and bars represent minimum and maximum values.

boarding activities were higher, in general, for students in the 2015 (Lecture + WB) term compared with the 2011 and 2012 (Lecture-Only) terms (Table 3). For concept mapping, there was a significant difference between the 2011 and 2015 terms ($P = 0.02$), as well as between the 2012 and 2015 terms ($P < 0.05$) ($F_{2,169} = 5.05$, $P = 0.007$, $\eta_p^2 = 0.06$). The model for comparing differences across the terms on scores related to interpreting a diagram category was not significant; therefore, pairwise comparisons were not examined ($F_{2,171} = 2.66$, $P = 0.07$, $\eta_p^2 = 0.03$). For using a mathematical formula, the differences were significant between the 2011 and 2015 terms ($P < 0.001$) ($F_{2,187} = 8.00$, $P < 0.001$, $\eta_p^2 = 0.079$). For mapping the sequence of events, the differences were significant between the 2011 and 2015 terms ($P < 0.001$), as well as between the 2011 and 2012 terms ($P < 0.01$) ($F_{2,171} = 12.09$, $P < 0.001$, $\eta_p^2 = 0.12$). Finally, for providing explanations using a diagram, there was a significant difference between the 2012 and 2015 terms ($P < 0.05$) ($F_{2,172} = 3.64$, $P = 0.03$, $\eta_p^2 = 0.04$).

Overall, results showed that both within and between groups, students in the 2015 term exhibited significantly greater performance on open-ended conceptual science questions for items corresponding to in-class whiteboard activities. Further evidence of gains in students' learning in the 2015 term included students' final course grades, where 82.50% students

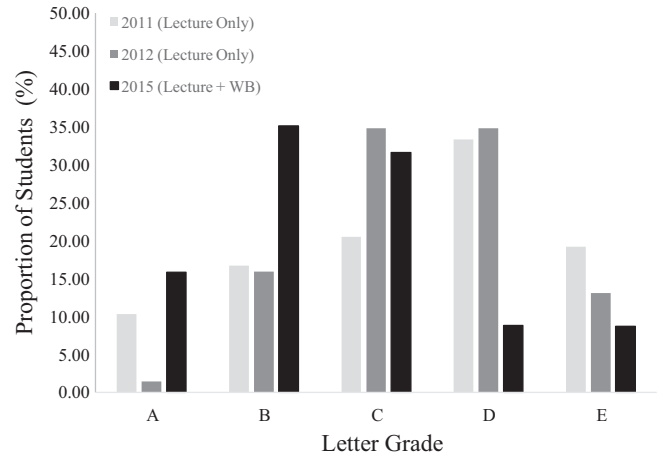


Fig. 2. Course grade distributions for the 2011 and 2012 (Lecture Only) and 2015 (Lecture + WB) terms.

received passing grades in 2015 (15.80% A, 35.10% B, and 31.60% C) compared with 52.10% in 2012 (1.40% A, 15.90% B, and 34.80% C) and 47.50% in 2011 (10.30% A, 16.70% B, and 20.50% C) (Fig. 2). Comparison of the groups showed that there was a significant difference in grades across the three terms ($F_{2,210} = 4.04$, $P < 0.05$, $\eta_p^2 = 0.04$), and post hoc tests showed that students in the 2015 term received significantly higher grades compared with students in the 2012 and 2011 terms ($P < 0.05$). There was no significant difference between the 2011 and 2012 terms ($P = 0.98$).

DISCUSSION

This study provides empirical evidence regarding the benefits of whiteboarding for deepening college students' understanding of complex physiology concepts. Results showed that when whiteboarding was incorporated in a lecture course, students demonstrated both deeper understanding of physiology concepts related to the whiteboard activities, as well as higher overall end of the term grades. Specifically, both within and between subjects, our findings showed that when whiteboarding was used in conjunction with lecture, students demonstrated more detailed and complete responses to open-ended problems that assessed mastery of advanced physiology concepts. Additionally, the course pass rate was ~50% in the two terms (2011, 2012) which were taught using lecture only. This passing course rate increased significantly to 82.5% in the term (2015) for which the same instructor combined lectures with whiteboards.

This work makes a novel contribution to the field, as it is the first known study to empirically investigate the effectiveness of the whiteboarding strategy in a university science course.

Table 3. Performance on short-answer exam items by type of whiteboarding activity

Type of Whiteboard Activity	2011	2012	2015
Concept mapping	38.01 (0.04)*	36.29 (0.03)†	53.26 (0.04)*†
Interpreting a diagram	53.65 (0.03)	54.42 (0.03)	62.34 (0.03)
Using a mathematical formula	62.42 (0.03)*	69.17 (0.03)	78.86 (0.03)*
Mapping the sequence of events	50.71 (0.04)*†	69.17 (0.03)*	73.37 (0.03)†
Verbal explanation with a diagram	55.59 (0.04)	51.35 (0.03)*	64.78 (0.03)*

Values are means ± SE in %. * †Matching symbols indicate significant between-group pairwise differences, $P < 0.05$.

Furthermore, unlike much of the existing laboratory research on retrieval-based learning, the assessment used to measure the learning outcome in this study represented higher order abilities representative of the university level knowledge and skills we aim to develop among college students. The outcome measured in this study aligns with the depth of understanding students are expected to demonstrate in advanced science courses (e.g., deconstructing complex problems, correctly applying science terminology, developing comprehensive scientific explanations).

The increased depth of conceptual understanding demonstrated by students on items that corresponded to the whiteboard activities can be explained by theory from the cognitive sciences regarding retrieval-based learning and the powerful effect of active recall for information retention (5, 6, 13, 20). In regards to the role of retrieval practice, whiteboarding serves as a useful tool to prompt students to actively recall disciplinary ideas presented in the lecture. Our findings are consistent with earlier, controlled experimental studies that demonstrated the positive effects of repeated retrieval (recall) for long-term information retention (3, 4), but extends this research by illustrating how retrieval practice can generalize to classroom-based applications. In addition, we draw from social constructivist frameworks that underscore the importance of discourse (e.g., peer-to-peer problem-solving) for deep understanding (2, 7, 11). Whiteboarding engages students in actively making sense of science ideas, applying scientific terminology and academic language as they engage with content, and critically examining and resolving discrepancies in their understanding of complex concepts through small-group and class discussions. While past studies indicate that even naive group discussions of multiple-choice clicker answers support students in arriving at greater conceptual understanding (2, 22), whiteboarding has the added benefits of allowing students to problem solve and represent complex ideas. These processes support students in developing scientific reasoning skills and fluency with scientific language, symbols, concepts, and principles (10, 11, 17). Finally, whiteboarding allows instructors to gauge students' emerging understanding of complex science ideas presented during the lecture, and to provide formative feedback and address misconceptions in real time (9, 16).

In addition, a closer examination of student performance on the Lecture + WB items showed interesting trends that have implications for how varied use of whiteboards may differentially support students' learning. Specifically, results showed that when the whiteboarding activity involved concept mapping (e.g., constructing a concept map of cardiac output) or describing a sequence of events (e.g., using a well-labeled diagram to show how glucose is moved from the lumen of the small intestine into the bloodstream), students in the 2015 term outperformed students in both the 2011 and 2012 terms. For whiteboarding activities that involved applying a mathematical formula to explain a concept (e.g., applying Kleiber's law to show how to calculate how many times greater the cat's absolute metabolic rate is compared with the mouse's) or developing an explanation using a diagram, students in the 2015 term outperformed students in only either the 2011 or the 2012 term. Finally, no significant differences across the three terms were found for performance on items related to the whiteboard activity that involved interpreting a diagram. These trends suggest that some types of whiteboard-

ing activities, such as concept mapping and describing a sequence of events, may be more effective compared with others, such as interpreting a diagram. However, it is important to note that these comparisons were exploratory, and there are a number of explanatory factors that could be influencing the documented differences in student performance across whiteboarding activity type. For instance, the format of the short-answer assessment items and/or differences in students' familiarity with certain whiteboarding activities are factors that were not examined in this study. Future studies are needed to systematically examine the effects of different types of whiteboarding activities, as well as to account for additional factors that may interact with the whiteboarding activities, to influence learning. Similarly, we propose at least three broad mechanisms (active retrieval, peer discourse, and instructor feedback) to explain the effectiveness of the whiteboarding activities, and future research is needed to study the relative contribution of each of these three mechanisms of student learning.

Based on the findings of this study and the related body of research (e.g., Refs. 8, 10, 21), there is a growing body of evidence that support faculty in reevaluating the sole use of didactic teaching approaches. Particularly, given research that repeatedly demonstrates the futility of reading and repetition of material for long-term retention (5–7), it is unlikely that the deep learning and meaningful sense-making we aim to support in university science classrooms is occurring when students are engaged almost entirely in rote learning through lecture-based courses. Of note, the findings from this study do not suggest that lectures should be eliminated entirely. In fact, our study examined a lecture plus whiteboarding condition against a lecture-only condition. Thus, in this study, we found that the combination of lectures (presentation of information on complex science topics) and whiteboarding (active recall and peer discussions) led to greater conceptual understanding. These findings are in line with past studies that point to lectures as a potentially effective way to present content when integrated with opportunities for students to actively engage with the lecture material (17, 23).

Finally, it is worth noting that the student sample in this study came from a university campus that serves a diverse student population, including a large percentage of students who are underrepresented in science, technology, engineering, and mathematics (STEM) fields (30–37% underrepresented minority students; 23–53% first-generation college students; 32–49% low-income students across the three terms examined). Furthermore, although the course size was smaller ($n = 49$) in the 2015 whiteboarding term (compared with $n = 78$ in 2011 and $n = 63$ in 2012), the demographic makeup of students in the 2015 term consisted of higher percentages of underrepresented groups in STEM by ethnicity, first-generation college students, and students from low socioeconomic status. Based on the student population from which we drew our sample, our findings have important implications for supporting science achievement among students who are at risk of dropping out of the STEM education pipeline, which, in turn, has implications for access into STEM career pathways (19). It is possible that whiteboarding mitigates some of the challenges documented among underrepresented students in STEM, including access to academic vocabulary and opportunities to engage in discourse around scientific concepts (11, 14, 18). In conclusion, there is an increasing need for scientists to emerge

from our universities with advanced conceptual and reasoning skills, and much of the onus for preparing future scientists lies in the hands of university science instructors. Our findings have important and immediate application value for science faculty to incorporate a relatively simple pedagogical strategy that may have powerful benefits for supporting students' mastery of disciplinary knowledge and preparation for future careers in science.

ACKNOWLEDGMENTS

The authors extend their gratitude to the middle school science teachers involved in the Integrated Middle School Science Partnership who inspired us to try whiteboarding with our students. The partnership was supported by the National Science Foundation under Grant DUE-0962804. We also thank to Dr. Danika LeDuc, who pioneered whiteboarding at California State East Bay in general chemistry courses, and Dr. Jenny Knight at University of Colorado Boulder, who provided valuable feedback on an early draft of the paper.

DISCLAIMERS

Any opinions, finding, and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

C.Y.I. and C.L.B. conceived and designed research; C.Y.I. performed experiments; C.Y.I., C.L.B., and K.N.H. interpreted results of experiments; C.Y.I. and C.L.B. prepared figures; C.Y.I. and C.L.B. drafted manuscript; C.Y.I., C.L.B., and K.N.H. edited and revised manuscript; C.Y.I., C.L.B., and K.N.H. approved final version of manuscript; C.L.B. analyzed data.

REFERENCES

1. **Anderson JR.** Problem solving and learning. *Am Psychol* 48: 35–44, 1993. doi:10.1037/0003-066X.48.1.35.
2. **Blasco-Arcas L, Buil I, Hernández-Ortega B, Sese FJ.** Using clickers in class. The role of interactivity, active collaborative learning and engagement in learning performance. *Comput Educ* 62: 102–110, 2013. doi:10.1016/j.compedu.2012.10.019.
3. **Bransford JD, Brown AL, Cocking RR.** *How People Learn: Brain, Mind, Experience, and School*. Washington, DC: National Academies, 1999, p. 51–78.
4. **Carpenter SK.** Cue strength as a moderator of the testing effect: the benefits of elaborative retrieval. *J Exp Psychol Learn Mem Cogn* 35: 1563–1569, 2009. doi:10.1037/a0017021.
5. **Carrier M, Pashler H.** The influence of retrieval on retention. *Mem Cognit* 20: 633–642, 1992. doi:10.3758/BF03202713.
6. **Cho KW, Neely JH.** The roles of encoding strategies and retrieval practice in test-expectancy effects. *Memory* 25: 626–635, 2016. doi:10.1080/09658211.2016.1202983.
7. **DeHaan RL.** The impending revolution in undergraduate science education. *J Sci Educ Technol* 14: 253–269, 2005. doi:10.1007/s10956-005-4425-3.
8. **Dobson JL, Linderholm T.** Self-testing promotes superior retention of anatomy and physiology information. *Adv Health Sci Educ Theory Pract* 20: 149–161, 2015. doi:10.1007/s10459-014-9514-8.
9. **Dunlosky J, Rawson KA, Marsh EJ, Nathan MJ, Willingham DT.** Improving students' learning with effective learning techniques: promising directions from cognitive and educational psychology. *Psychol Sci Public Interest* 14: 4–58, 2013. doi:10.1177/1529100612453266.
10. **Duschl R.** Science education in three-part harmony: balancing conceptual, epistemic, and social learning goals. *Rev Res Educ* 32: 268–291, 2008. doi:10.3102/0091732X07309371.
11. **Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP.** Active learning increases student performance in science, engineering, and mathematics. *Proc Natl Acad Sci USA* 111: 8410–8415, 2014. doi:10.1073/pnas.1319030111.
12. **Furtak EM, Seidel T, Iverson H, Briggs DC.** Experimental and quasi-experimental studies of inquiry-based science teaching: a meta-analysis. *Rev Educ Res* 82: 300–329, 2012. doi:10.3102/0034654312457206.
- 12a. **Giuliodori MJ, DiCarlo SE.** Myelinated vs. unmyelinated nerve conduction: a novel way of understanding the mechanisms. *Adv Physiol Educ* 28: 80–81, 2004. doi:10.1152/advan.00045.2003.
13. **Karpicke JD, Blunt JR.** Retrieval practice produces more learning than elaborative studying with concept mapping. *Science* 331: 772–775, 2011. doi:10.1126/science.1199327.
14. **Laurillard D.** *Rethinking University Teaching: A Conversational Framework for the Effective Use of Learning Technologies*. New York: Routledge, 2013.
15. **Linderholm T, Dobson J, Yarbrough MB.** The benefit of self-testing and interleaving for synthesizing concepts across multiple physiology texts. *Adv Physiol Educ* 40: 329–334, 2016. doi:10.1152/advan.00157.2015.
16. **Megowan-Romanowicz C.** Whiteboarding: a tool for moving classroom discourse from answer-making to sense-making. *Phys Teach* 54: 83–86, 2016. doi:10.1119/1.4940170.
17. **Montrezor LH.** Performance in physiology evaluation: possible improvement by active learning strategies. *Adv Physiol Educ* 40: 454–457, 2016. doi:10.1152/advan.00022.2016.
18. **Newell A, Simon HA.** *Human Problem Solving*. Englewood Cliffs, NJ: Prentice-Hall, 1972.
19. **Reardon SF, Galindo C.** The Hispanic-white achievement gap in math and reading in the elementary grades. *Am Educ Res J* 46: 853–891, 2009. doi:10.3102/0002831209333184.
20. **Roediger HL III, Karpicke JD.** The power of testing memory: basic research and implications for educational practice. *Perspect Psychol Sci* 1: 181–210, 2006. doi:10.1111/j.1745-6916.2006.00012.x.
21. **Smith MA, Roediger HL III, Karpicke JD.** Covert retrieval practice benefits retention as much as overt retrieval practice. *J Exp Psychol Learn Mem Cogn* 39: 1712–1725, 2013. doi:10.1037/a0033569.
22. **Smith MK, Wood WB, Adams WK, Wieman C, Knight JK, Guild N, Su TT.** Why peer discussion improves student performance on in-class concept questions. *Science* 323: 122–124, 2009. doi:10.1126/science.1165919.
23. **Tsang A, Harris DM.** Faculty and second-year medical student perceptions of active learning in an integrated curriculum. *Adv Physiol Educ* 40: 446–453, 2016. doi:10.1152/advan.00079.2016.
24. **van den Broek GS, Takashima A, Segers E, Fernández G, Verhoeven L.** Neural correlates of testing effects in vocabulary learning. *Neuroimage* 78: 94–102, 2013. doi:10.1016/j.neuroimage.2013.03.071.