Renovating Cell Biology Class with Principle-Oriented Resources in Pedagogically Structured Learning Environment

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Abstract

This article presents a renovation effort to improve the structure and pedagogy of instruction of upper-division cell biology education at a minority-serving urban university with five thousand undergraduate students majoring in biology. In the reforming of structure, we revamped major cell biology contents into Principle Oriented Resources (POR) by explicitly connecting those topics with an overarching principle of protein regulation. While trying to provide a pedagogically conducive learning environment, we adopted the practices of inquiry-based learning, project-based learning, and collaborative learning. After taking in a pedagogically structured environment (PSE) for a summer and a fall semester courses, we compared the outcomes of POR-PSE with the same outcomes of a traditional summer and a traditional fall course. We found significant positive results of POR-PSE from both summer and fall courses, providing policy implication to renovate STEM education as well as biology education.

Keywords: *College Biology,* ***Inquiry-based learning,*** *Renovating Learning Environment, Principle Oriented Resources, Pedagogy of Instruction,* ***Biology Education***

Introduction

The need to improve undergraduate biology education has been widely recognized across the universities of the US (Andrews, et al., 2012; Johanns, Dinkens, & Moore, 2017). One of the consensuses emerged from the field of biology education is to identify a few core concepts of biology which can transform biology from descriptive to a principle-centered STEM science (Kramer & Thomas, 2006). As a consequence of the reforming effort, five core concepts were adopted by the biology association: evolution, transformations of energy and matter, information flow, structure and function, and systems (Brownell, Freeman, Wenderoth, & Crowe, 2014).The first two concepts, evolution and transformations of energy and matter, are generally covered in courses like Ecology, Evolution, and Biochemistry. The other two, information flow, structure and function, and systems, are mainly taught in Genetics, Physiology, and Cell Biology. In addition to the identification of the five core concepts of Biology, there have been serious efforts to improve teaching each discipline (Bierema et al., 2017; Kramer et al, 2012; Nelson, 2008; Wilson et al., 2006).

However, an effective implementation of these concepts to the practice of teaching invites pedagogically designed new teaching resources that could explicitly reveal and connect the implicitly embedded five core concepts in those upper division biology courses mentioned above. Students are likely to be able to effectively apply those concepts to their learning contents only when they are nurtured in the proper pedagogically designed learning environments (Kay & Kibble, 2016).

One of the current difficulties in STEM teaching is the lack of sufficient resources that can explicitly expose the presence of an overarching principle in each chapter of cell biology where students often face details of molecular mechanisms (O'day, 2006). These five new concepts are likely taught in the introductory chapter in abstractive forms and the contents of the following chapters often remain disconnected from each other.

Most of current cell biology textbooks contain the chapter concerning information flow, often named cell communication or signal transduction, at the second half, which is not only far too late for an in-depth understanding of the course, but also too abstractive for students to use as a tool to better understand other topics (Alberts et al., 2013; de la Fuente-Arias, 2017; Hardin& Bertoni, 2018; Karp, Iwasa, & Marshall, 2016; Johanns, Dinkens, & Moore, 2017).In the traditional cell biology classrooms, the cell-biology concepts, inevitably, remain in the realm of diverse and disconnected topics of cellular structures and functions (Yates & Marek, 2015). Needless to say, the absence of explicit guidance to connect the contents with an overarching principle has been a leading cause for many students to perceive cell biology as a descriptive discipline and obtain their knowledge largely through rote memorization (Shi et al., 2010).Furthermore, the cell communication chapter is loaded with abstractive concepts that not only demands the memorization of numerous names and the functions of proteins but also includes seemingly contradictory functions mediated by antagonizing proteins (Queloz et al., 2017). For example, the most cell biology textbooks include chapters describing how a signal directs cells to proliferate or inhibit programmed cell death (without proliferation) with no explicit explanation of how cells choose one of these mutually exclusive responses. Inevitably, simple rote learning will lead to contradictory conclusions that will obscure students' understanding and thus prevent them from exerting higher order thinking and constructing hierarchical structures between different topics of cell biology (Sorgo & Siling, 2017).

In addition, the five core concepts are frequently interconnected with each other and thus overly complicated to the students. For example, when the students are introduced in cell biology that the process of tumorigenesis initiates by disturbances of a specific and critical information flow that controls cell cycle, they also learn that certain mutations are critical to convert the typical structure of several proteins to aberrant and tumorigenic form. These learning contents are packed with numerous and strange names of proteins, for example, Son of Sevenless, and various molecular mechanisms associated with the dysregulation of the pathway and aberrant transitioning of the structure of the key proteins. A simple sentence that summarizes all these complicated explanations is that the regulation of protein structure directs protein function, which in turn controls the information flow. Thus, we prioritized the protein structure and function as the leading organizing concept for the five core concepts of biology and developed new learning resources and implemented to upper division cell biology courses with approximately 150 students.

Although thousands of different proteins function in a cell, there is a much smaller number of proteins control much larger groups of proteins and these regulatory proteins are generally orchestrated through only a few types of mechanisms: phosphorylation or with a specific association of adenine or guanine nucleotides (Gherardini, Ausiello, Russell, & Helmer-Citterich, 2010; Kramer & Thomas, 2006; Mulnix, 2003). For example, cancer cells can arise when a few key proteins change their structure and function. These key proteins are regulated through phosphorylation and association with guanine nucleotide (Wood, et al., 2007). With this guiding principle, we developed new learning resources threaded through the principle of protein regulation.

With the recognition of the limitations of traditional biology learning practices and the goal of renovating cell biology learning with the newly identified core concept described above, we have created innovative principle-oriented resources (POR) in a pedagogically structured environment(POR-PSE) for cell biology class. The POR-PSE was spearheaded by the series of the pedagogically renovated principle-oriented lectures focused on the core concepts. In the traditional classroom, students are supposed to absorb content-centered lectures that are a reiteration of anecdotal arrays of historical, scientific findings. In our innovative course, the instructor first outlined the new learning plan and restructured the traditional lecture into principle-oriented one.

To build a project-based and collaborative learning environment, we developed multiple assignments of building core-concept centered learning videos for each chapter of the cell biology course. By adopting project-based learning, students designed and carried out their own project to answer their questions and come to conclusion. Having collaborative learning, students work together in a small group to solve a problem, helping each other (Ben-Zvi, 2007; Cole, 2009; Tishkovskaya & Lancaster, 2012; Wright & Boggs, 2002).

The best part of POR-PSE learning environment is to nurture students to uncover the unifying core concept of cell biology and organize diverse cell biological topics with the guiding principle in a healthy educational setting (Doménech-Betoret, 2018). In addition to the pedagogically renovated principle-oriented lectures focused on the core concepts, the POR-PSE also includes additional interventions.

To guide students asking questions to discover knowledge for themselves and achieve a deeper understanding, we developed over hundred new clicker questions and implemented into the class. With the implementation of these well-accepted instructional strategies, we transformed the passive learning environment of the traditional cell biology course to actively engaged learning.

Restructuring Biology Course

Understanding cell biology through the principle of protein regulation

To renovate the traditional content-centered cell biology class to a student-centered, active learning environment, we took several steps. We categorized traditional cell biology contents into ones that are taught best in cell biology and others that are taught more in-depth in the classes of genetics, molecular biology, and biochemistry. We also restructured the core topics of cell biology by implementing the principle of protein regulation - a unifying principle of cell biology. One way of defining life is that it is a principle that is considered to underlie the distinctive quality of animate being (O'day, 2006, 2007). The distinctive quality of animate being would include metabolism, growth, reproduction, and adaptation to the environment. These various events are executed by cells and eventually by proteins at the molecular level. Most of these proteins that are involved in the above-mentioned functions have a fixed three-dimensional structure and thus maintain an invariable state or function. In order to have a change, whether it is an adaptation to environmental changes or decision to grow, cells need a way to change the behaviors of proteins. There are three major ways of changing protein behaviors: phosphorylation and association with either adenine or guanine nucleotides often lead to significant changes in properties and behaviors of proteins. These changes include direct activation of defined protein activity, subcellular localization, and/or stability.

Adopting Inquiry-Based Learning for principle-based knowledge

To guide students' internal construction of principle-based knowledge network, we created a series of in-class activities in the light of Inquiry-Based Learning. Inquiry-Based Learning (IBL) is an active learning approach that focuses on questioning, critical thinking and problem-solving—the abilities needed for and developed through education. The primary goal of IBL is to have students discover knowledge for themselves, achieve a deeper understanding, and become highly knowledgeable about particular topics (Cole, 2009; Yu, Liu, & Chan, 2005). Instructors' skill in the plan and delivery of IBL in biology with technology is critical to student success (Juliana, 2002). The technology tools best support learning when integrated with teaching techniques, curriculum, and assessments (Means & Haertel, 2004). The study conducted by Wentworth and Monroe (2011) assessed the integration of technology in course activities based on the following criteria: 1) lessons involved the students themselves in actively using technology, 2) the technology was integral, not peripheral, to the leaning activity, 3) the lesson focused on the concept, not the technology, and 4) the technology facilitated learning activities that would be more difficult or impossible for the students to accomplish without technology. The results showed that after instruction, the instructors showed high levels of proficiency based on the stipulated criteria.

To guide students' internal construction of principle-based knowledge network (de la Fuente-Arias, 2017), we created series of in-class activities that would recapitulate the presence of the principle of protein regulation in the entire topics of cell biology. Students were guided and reminded of the principle of protein regulation in every class throughout the semester. As an ice-breaking activity, they were often asked to identify the core regulatory proteins in each topic that are regulated by one of the three main ways, i.e., phosphorylation, ATP, or GTP binding. Instead of memorizing a certain protein happens to be phosphorylated or associates with certain nucleotide under certain circumstances, students were guided to realize that a system needs a push to initiate a change or produce a result different from what it usually is or does. In this way, students were primed to identify what could function as a push that can initiate a change in a system. Group discussion was encouraged during the in-class activities, but the evaluation was based on the individual clicker and exam performances. Student participation was encouraged by giving 50% credit on the participation and 50% on a correct answer for each activity.

Digital Learning via Project-Based Learning and Collaborative Learning

To further facilitate students' higher order thinking activities, "digital learning animation projects" on major topics of cell biology were developed. Development of these projects was inspired by two pedagogical approaches - Project-Based Learning (PBL) and Collaborative Learning(CL).

Project-Based Learning (PBL) is an instructional approach that involves students in finding answers for their own questions, designing and carrying out their own plan to find the answer, collecting and analyzing data, and making conclusions and producing artifacts to represent their own learning (Blumenfeld et al.,1991). PBL has been recommended as one of the important pedagogical approaches to reform statistics education (Franklin & Garfield, 2006; Tishkovskaya & Lancaster, 2012). Melton and others (1999) showed the potential of PBL in promoting education outcomes for Hispanic and Black students.

Baglin and others (2012) exhorted teachers to pair PBL with technology, and Bulmer and Haladyn (2011) presented a good example of utilizing simulation technique to produce learning outcomes for successful PBL. In Collaborative Learning(CL), students can work together to solve a problem, aiding and learning from each other, thus promoting individual learning further (Dillenbourg, 1999). In a similar vein, Perkins and Saris (2001) found that CL was an effective method to promote thinking skills as well as other important skills, such as conceptual understanding and critical thinking. Moreover, CL was effective in turning passive students into active learners of statistics. To implement CL successfully in biology education, instructors play an important role. They should be familiar with and support the use of CL for the content (Ben-Zvi, 2007) and take a proactive role during group interactions to maximize learning (Delucchi, 2006).

Students were given certain proteins that are either being able to be phosphorylated, associated with ATP or GTP. The projects were to generate a Power Point file showing how these proteins change from inactive state to active and thus induce events subsequent to that as a series of events. Through this additional learning opportunity, students actively exercised and developed higher order thinking skills as well as the rote recalling of the key regulatory proteins.

Methods and Research Questions

Participants

The study participants were 458 college students who enrolled in cell biology courses as their major requirement course at a large urban university located in south Florida during summer and fall semesters of 2017 and 2018. As shown in Table 2, 64 students in summer 2017 and 138 students in fall 2017 learned cell biology in traditional settings, while 111 students in summer 2018 and 145 students in fall 2018 took the same course in new learning environments. Table 1 also presents the students' sex and race composition of four courses. More than 64% of female students across the four courses enrolled in cell biology. Among the racial groups, Hispanic students were the highest group, followed by Black, White, and Asian students.

Table 1. Frequencies of participants' sex and racial groups

	Sex		**Race**				**Total**
	Male	**Female**	**White**	**Black**	**Hispanic**	**Asian**	
2017 Summer	19 (29.7%)	45 (70.3%)	16 (25.0%)	21 (32.8%)	24 (37.5%)	3 (4.7%)	64 (100%)
2018 Summer	29 (26.1%)	82 (73.9%)	17 (15.3%)	13 (11.7%)	75 (67.6%)	6 (5.4%)	111 (100%)
2017 Fall	49 (35.5%)	89 (64.5%)	13 (9.4%)	9 (6.5%)	105 (76.1%)	11 (8.0%)	138 (100%)
2018 Fall	43 (29.7%)	101 (69.7%)	26 (17.9%)	18 (12.4%)	89 (61.4%)	11 (7.6%)	145 (100%)

Performance Assessments

To examine the effectiveness of the principle-oriented resources in a pedagogically structured environment (POR-PSE) to educate cell biology, we implemented POR-PSE to a minority-serving urban university with five thousand undergraduate students majoring in biology during the summer semester and a fall semester in 2018. The performance outcome of POR-PSE was compared with the same outcome of the traditional biology courses at the same institution during a summer semester and a fall semester of 2017.

We examined the outcomes of clicker question, assignments, and final examination results. Analysis of students' performance on the clicker question and assignments results allowed the instructor to identify concepts that require further guidance.Final examinations of each semester students typically consisted of 40 multiple choice questions of rote memorization, questions requiring correct but simple concepts, and higher-level questions with critical thinking abilities.

Common higher-level questions were strategically included across the semesters to assess students' learning gains. The final examination composed of ten items during the summer courses (2017 and 2018) while it had 17 items during the fall courses (2017 and 2018). After assigning one point for the correct answer of each item and zero point for the incorrect answer, the scores of all items were averaged and used for the analyses. The range of the outcome variable was .10 to 1.00.

Having renovated courses in structure and pedagogy, we attempted to answer the following research questions through this project:

1. Are the students' performances in the POR-PSE courses better than those in the traditional biology courses?
2. Do the low performers (students of 25% percentile) in the POR-PSE perform better than the counterparts in the traditional biology courses?
3. Are there differential effects of the POR-PSE for sex or minority status?

Results

Students' performances of traditional and POR-PSE courses

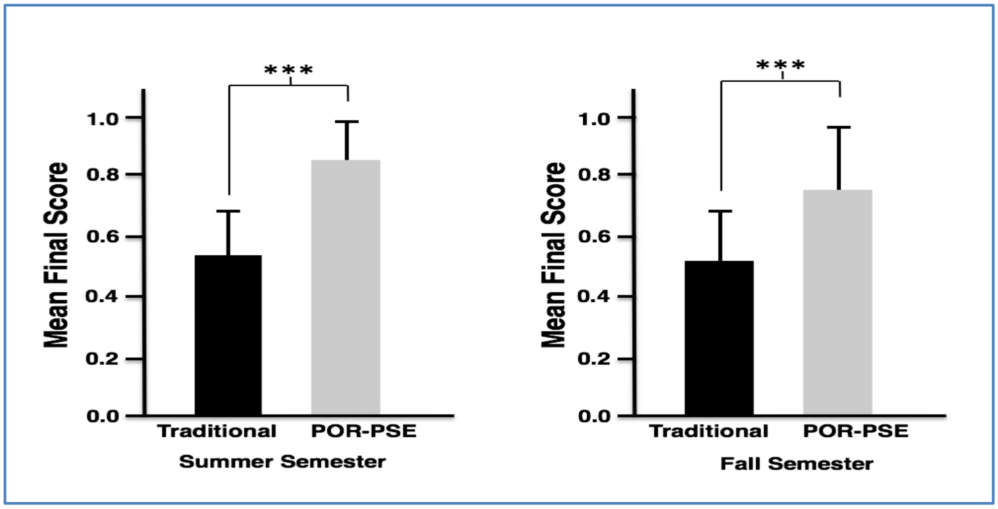
We found that acquisition of diagnostic data and their feedback implementation as students-centered in-class activities empowered students to overcome misconceptions, developed higher order thinking skills, enriched existing knowledge, and constructed traces between distinct topics of cell biology. We further scaffolded students to construct the overarching principle of the protein regulation by assigning multiple projects of generating learning-animations on major topics of cell biology. We also discovered that the final examination results in POR-PSE courses were significantly higher than traditional courses.

We conducted two series of statistical analyses using the final examinations: One set is for all students and the following set is for low performing students. In the first analysis for all students, the two summer courses (2017 and 2018) were compared to examine the effectiveness of POR-PSEin similar conditions (summer semesters). In the subsequent analysis, the two fall semesters (2017 and 2018) were also compared for all students.As Table 2 and Figure 1 present, in both summer and fall courses, the students of POR-PSEproduced significantly higher outcomes than those in the traditional methods. In the summer courses, the mean of POR-PSE(M = .86, SD = .13) was significantly higher than that of the traditional course (M = .54, SD = .14). With equal variances assumed (Levene's F = .81, $p > .05$), the independent sample T-test displayeda significant T-value of 5.92 ($p < .01$). For the fall courses, the mean of POR-PSE(M = .74, SD = .20) was also significantly higher than that of the traditional method (M = .51, SD = .17). With equal variances not assumed (Levene's F = 8.35, $p < .05$), the T-value was 10.28 ($p < .01$).

Table 2. Comparison of all students of traditional and POR-PSE courses

	Traditional	**POR-PSE**		
	Mean (SD)	**Mean (SD)**	***T-Test***	***p***
Summer	.54 (.14)	.86 (.13)	15.92	.00
Fall	.51 (.17)	.74(.20)	10.28	.00

Figure 1. Comparison of overall students' achievement in traditional and POR-PSE courses at summer and fall semesters.

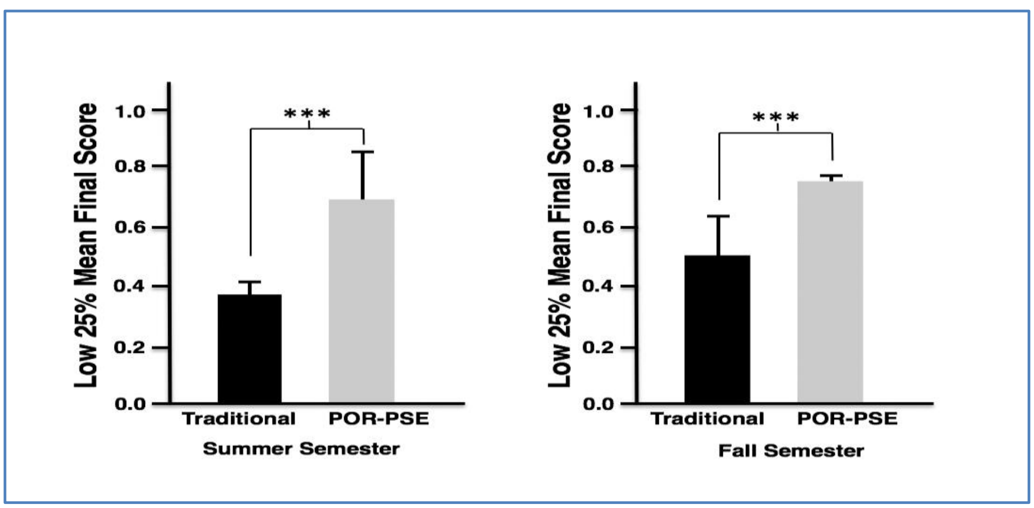


In the subsequent analysis for low performing students from two courses consistently confirmed the significantly high performances of POR-PSE (see Table 3). During the summer courses, POR-PSE students (*M* = .67, *SD* = .11) outperformed traditional course students (*M* = .33, *SD* = .03) with T-value of 13.95 (p <.01) with a slight violation assumption of homogeneity (Levene's $F = 5.17$, $p = .03$). For the fall courses, POR-PSE students (*M* = .51, *SD* = .11) consistently outperformed traditional course students (*M* = .34, *SD* = .09) with T-value of 8.44 (p <.01) without violating homogeneity of assumption (Levene's $F = 3.25$, $p > .05$).

Table 3. Comparison of low performing students (25 percentile) of traditional and POR-PSE courses

	Traditional	**POR-PSE**		
	Mean (SD)	**Mean (SD)**	***T-Test***	***p***
Summer	.33 (.03)	.67 (.11)	13.95	.00
Fall	.34 (.09)	.51(.11)	8.44	.00

Figure 2. Comparison of low performing students' (25 percentile) achievement in traditional and POR-PSE courses at summer and fall semesters.



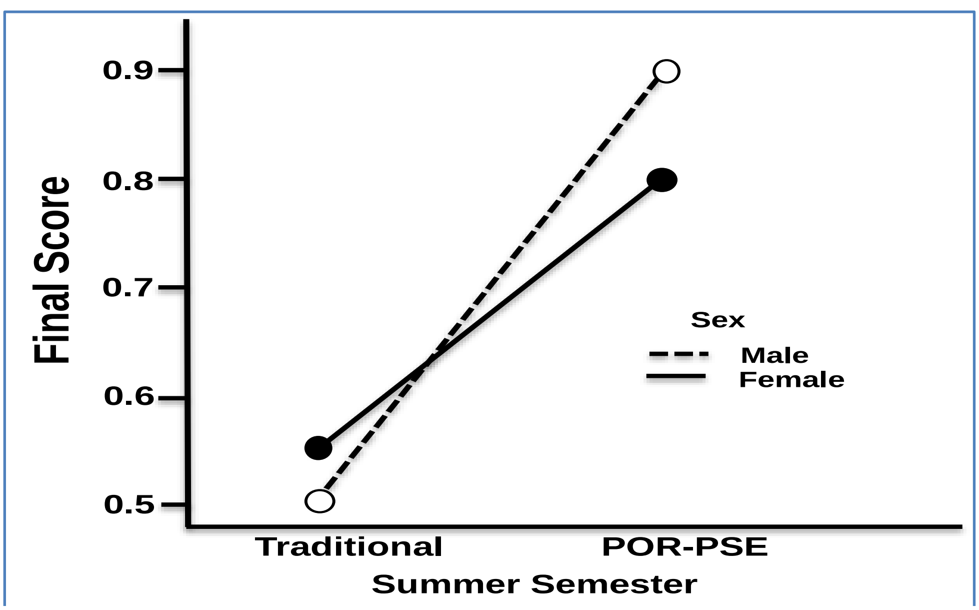
In the examination of differential effects of POR-PSE for sex and minority status as well as the main effect of POR-PSE (Table 4), we conducted generalized linear modeling (GLM) and present the results in Table5. Consistent with the independent samples T-tests, the GLM results revealed that students in POR-PSE coursesdemonstrated significantly higher performances than those in the traditional methods in both summer (F = 101.90, p< 0.01) and fall (F = 48.20, p< 0.01).

Table 4. Results of generalized linear modeling

Summer	**Source**	**F**	**Sig.**	**R-Square=.65**
	POR-PSE	101.90	0.00	
	Sex	0.56	0.46	
	Minority	1.18	0.32	
	POR-PSE*Sex	4.70	0.03	
	POR-PSE*Minority	0.95	0.42	
	Sex*Minority	1.65	0.18	
	POR-PSE*Sex*Minority	1.38	0.25	
Fall	**Source**	**F**	**Sig.**	**R-Square=.31**
	POR-PSE	48.20	0.00	
	Sex	0.05	0.82	
	Minority	0.99	0.40	
	POR-PSE*Sex	0.08	0.78	
	POR-PSE*Minority	0.52	0.67	
	Sex*Minority	1.26	0.29	
	POR-PSE*Sex*Minority	1.14	0.33	

Another notable outcome from GLM was a significant interaction effect of POR-PSE and sex (F = 4.70, p< 0.05). As shown in Table 4 and Figure 3, in the traditional classroom, female students performed better than male students. In POR-PSE, male students showed higher performance than female students. We did not observe any effect of the minority status or other interaction effects.

*Figure 3.*The POR-PSE course effect interacting with sex



Discussion

The purpose of this paper was to provide detailed descriptions of our renovation of undergraduate biology education.

Realizing the limitations of current, traditional biology courses, we have created innovative principle-oriented resources in a pedagogically structured environment(POR-PSE) for cell biology class. While students in a traditional course learn passively in content-centered lectures, in our POR-PSE, we restructured the lecture into principle-oriented one. Besides, we implemented inquiry-based learning activity by having problem-solving clicker activities, project-based learning by providing multiple assignments of building core-concept centered learning videos, and collaborative learning by letting students work together in a small group to solve a problem.

Importantly, our effort to adopt interactive technology was adequately efficient. Current student populations are grown up in an environment where audio-visual technologies dominate. As such, several investigations indicated that students' learning gains are significantly higher when they learn with teaching animations compared to the traditional static images and graphs (O'Day, 2006, 2007; Stith, 2004). Actual production of decent scientific animation does not require professional graphics software. A previous study demonstrated that a PowerPoint platform is enough for generating teaching animations for signal transduction (O'Day, 2006). The students were expected not only to master rote learning of the key proteins but also to construct a procedural knowledge network in a guided, yet autonomous manner by engaging in the assigned projects.

As several researchers (Ben-Zvi, 2007; Cole, 2009; Tishkovskaya & Lancaster, 2012) noted, in the new learning environment (POR-PSE), we were able to nurture students to build up the unifying core concept of cell biology and organize diverse cell biological topics with the guiding principle in a comfortable, interactive educational contexts. Most of all, we were successfully able to transform the passive learning the traditional cell biology course to an actively engaged learning environment.

In the design and analysis of the effectiveness of our POR-PSE, we compared two sets of analyses for POR-PSE courses comparing traditional courses in large upper division cell biology instructions. We first adopted POR-PSE in summer 2018 and compared the POR-PSE outcomes with a traditional summer course of 2017, and in the following fall semester (fall 2018), we implemented POR-PSE and compared the results with those of traditional fall course (fall 2017).

The learning performances of the two groups (POR-PSE vs. traditional) were evaluated with the outcomes of clicker question, assignments, and final examination results which composed of common subsets of questions that require higher-level thinking ability in addition to the foundational rote memorization of the contents. As we presented earlierin Table 3 and Figure 1, the students of POR-PSE courses demonstrated significantly higher performances in both summer and fall semesters.

The summer courses are substantially shorter than fall course (seven weeks vs. four months) and the students of summer courses equally challenged with the same amount of learning contents that require higher level thinking capacity. Despite the challenges of the summer course, the learning outcomes as good as those of fall courses. In other words, POR-PSE settings were effective regardless of the duration or the settings.

We also paid attention to the effectiveness of POR-PSE for low performing students in an effort to break new ground for those who lag behind in biology learning. We confirmed the conspicuous effects of POR-PSE for students of 25 percentile in both summer and fall courses as we presented in Table 3 and Figure 2. In our extra analysis, we also found the high performing students (top 25 %) also significantly higher performance in POR-PSE than traditional settings although we did not provide the specific results. We also noted the high increase in the learning performance from the questions that demand high- level thinking. Thus, the new learning environment of POR-PSE revealed significant outcomes in leading better learning performance across all levels of the students' performance.

As introduced previously, our research setting was a minority serving university in which the majority of students were minorities, taking up more than 70 percent. The students' learning performance was significantly improved across all racial groups. When learning outcomes measured from the examination scores concerning minority status, any significant differential effects of POR-PSE for minority students were not noted. However, as shown in Table 4 and Figure 3, we noted a significant interaction effect between POR-PSE and sex in summer. Male students' performance was lower in traditional learning environment but significantly higher in POR-PSE courses. We attributed this result to the fact that male students tended to be more attentive to the immediate win-lose stimulations of clicker questions. Only the POR-PSE courses included clicker question activities.

Providing empirical evidence of POR-PSE in teaching upper-division cell biology education, we hope that our results exhort STEM educators and policymakers to come up with effective, innovative instructional modes. At the same time, we wish to call attention to future efforts.

The POR-PSE cell biology course was focused to renovate core cell biology topics, and thus the topics that overlap with Genetics, Molecular Biology, and Biochemistry were not included. In the future, we wish to see POR-PSE courses expanded to these other courses, which will promote more smooth connection of the upper-level biology courses. Most of all, students will have a better grasp of the overarching principle in various upper-division biology courses.

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