Abstract Title Page

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Title: Regular Biology Students Learn like AP Students with SUN

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Abstract Body

Limit 4 pages single-spaced.

Background / Context:

Life is powered by the basic processes of biological energy transfer. These processes include: 1) *photosynthesis* (PS) by which "food" and oxygen for most living things is made and 2) c*ellular respiration* (CR) by which some energy is transferred from them to ATP. ATP is the chemical energy currency used by all living things to power the activities we call "life."

Decades of research have documented student confusion regarding biological energy transfer, which has been identified as a cross-cutting concept and educational priority in multiple policy documents (NRC, 2012; NGSS, 2013; DOE, 2014). Recently, Andy Anderson's group reported that only 10% of high school students became committed after instruction to tracing matter and energy in carbon-transforming processes (Jin and Anderson, 2012). However, we fear a new 'tracing tool' developed to remedy this situation (Dauer et al., 2014) will create difficulties when students attempt to transfer their understanding of energy to other disciplines. As specified by the Next Generation Science Standards for PS and CR, this tool scaffolds declarative knowledge of conservation of matter and energy with no rationale for *why* or *how* this occurs in living things. In addition, the tool's use of twist ties on 'bonds' of carbon compounds to indicate 'energy' appears to support multiple misconceptions including: energy is separate from the interactions of matter (Quinn, 2014), energy exists alone in a fuel, and that energy is found in bonds. That last idea makes it difficult for chemistry students to learn that energy must be *added* to break *all* bonds (Cooper and Klymkowsky, 2013). Our biological energy transfer pedagogy also uses models, but it provides a rationale for both *why* and *how* this occurs, which should encourage the belief that life depends upon physical laws (Barak, 1997, 1999). Here we report significant long-term effects of this approach upon student learning and briefly introduce how it is uniquely positioned to support a coherent presentation of energy across disciplines.

Purpose / Objective / Research Question / Focus of Study:

The SUN approach to biological energy transfer education is fundamentally different from past practices that trace chemical and energy inputs and outputs. The SUN approach uses a hydrogen fuel cell to convince learners that electrons can move from one substance to another based on differential attraction. With a hydrogen fuel cell, learners can see a propeller turning when only hydrogen and oxygen gases are present. The movement of electrons from the hydrogen fuel to the oxygen acceptor is supported with an animation of the invisible electron transfer and resultant products made. Living things run on microscopic fuel cells called mitochondria where the electron donor is food and the ultimate acceptor is oxygen. The SUN Project scaffolds understanding of this process with physical and digital manipulatives. Students configure nested trays with moveable components so as to enact the salient processes that transfer matter and energy in the mitochondrion. Energy is harvested not in the turning of propellers, but in the eventual rotation of a nanomachine that produces a chemical essential for life called ATP. SUN scaffolds include a mechanically manipulated replica with supporting animations. Food making in chloroplasts depends upon light to initiate electron movement. The materials show that many of the intervening processes mimic those in the mitochondrion.

The purpose of this cluster, randomized controlled trial (RCT) was to determine the *long-term* efficacy of the SUN Project intervention on student understanding regarding *why* and *how* CR and PS occur. Students participated in regular biology classes within schools randomly assigned to either the treatment (T) or control (C) condition. At the same time the achievement of a small group of AP biology students who did not use the SUN materials provided another meaningful context for interpreting outcomes. The research questions (RQ) of this project asked during the first year were:

- *RQ1*. Does the SUN Project significantly impact long-term student learning?
- *RQ2*. Does the SUN Project significantly impact student confidence in their understanding?
- *RQ3*. What variables moderate student outcomes?
- *RQ4*. How much do SUN vs. Control students value their instructional materials?
- *RQ5*. How do the outcomes of treatment students compare to that of a small group of AP biology students who are not using the SUN materials?

Setting:

This cluster RCT was conducted for one year in primarily Wisconsin high schools. About half of the schools were rural while ~30% of the schools had <80% white population. The AP group also included rural/non-rural and ethnically varied schools. Only one teacher participated from each school with two exceptions: there were two similar "urban" schools that each contained two participating teachers with one school assigned to each group (T and C).

Population / Participants / Subjects:

Approximately 24% of assigned teachers declined participation before the study began. (Please see "Results" for evidence of initial T and C equivalence nonetheless.) Once begun, the subjects were 779 high school students in one regular biology class of each of 38 participating teachers. Because one control class was excluded for a pretest administration error, 19 treatment and 18 control teachers with 770 students ultimately participated. Schools were matched by high school freshman class size and ethnic makeup before random assignment. Because all except two schools fielded one regular biology teacher, randomization was essentially by teacher. To minimize bias toward high achievers, teachers designated which class would participate prior to the start of the school year. Seven AP biology teachers with 115 students provided another type of comparison. While not part of the RCT, they provided some meaning to any gains achieved.

Intervention / Program / Practice:

Treatment group teachers attended the summer SUN workshop for two weeks during which they significantly improved both their knowledge and self-efficacy with very large effect sizes, even one year later (Batiza et al, 2013). During the workshop, the teachers became familiar with these materials and revised their curricula for the coming year, incorporating only what they found valuable. *All* teachers deposited implementation data online every two months and were supported with regional meetings twice a year. In the classes of treatment and control group teachers as well as in the classes of a small group of AP biology teachers, tests (that teachers were asked not to examine) were administered at the beginning and end of the year. Project staff visited each classroom in order to collect student evaluations of teaching materials used and to provide support. Control teachers and AP biology teachers attended the workshop at the end of the year as compensation. Data was collected for another year when all were using the SUN materials, but this paper deals only with the first year, which constituted the cluster, RCT.

Research Design:

During the first year, a cluster, RCT was conducted regarding the effectiveness of the SUN curriculum vs. 'business as usual controls." The small AP group served as an additional comparison group to help determine the meaning of outcomes. The pre/post assessments included both a multiple choice (MC) assessment on CR and PS and a drawing with explanation assessment regarding CR. Table 1 shows the MC post assessment core understandings mapped to the Bloom's Taxonomy level of the 20 items (Please insert Table 1). The 7 core concepts addressed CR and PS and their comparison to each other and to a hydrogen fuel cell. Item analysis indicated high validity and difficulty; 35% of items required higher level thinking skills.

Data Collection and Analysis:

Pre and post student data was collected unexamined by the teacher and mailed to the PI. Data was coded into SPSS files by undergraduate and graduate assistants overseen by the lead evaluator. HLM analysis was conducted by HLM an expert with SAS PROC MIXED.

Findings / Results: (please insert Table 2 here)

Descriptive statistics. Based on the 770 participating regular biology and 115 AP students (excluding the 9 non-participants as above), missing variables varied between 3% and 13%. See Table 2 for the computed means and standard deviations of the variables broken down by treatment. Table 2 shows the treatment and control groups were initially equivalent in terms of previous GPA, multiple choice (MC1) and drawing (DR1) content assessments, confidence in their answers (CNF1), and gender distribution (Please insert Table 2). Similarly, treatment and control group teachers had equivalent prior knowledge and self-efficacy (Batiza et al., 2013). Correlations among the variables of analysis are presented in Table 3. (Please insert Table 3.)

RQ1 & 2: Does the SUN Project significantly impact student learning about CR and PS, and confidence in responses? Because students were nested within teachers, hierarchical linear models (HLM) were used to test the treatment effect (Model 1, Table 4). (Please insert Table 4.) The dependent variables of the HLM analyses were (1) students' post multiple choice scores based on 20 items, (2) students' post drawing scores, and (3) students' post confidence scores. The control variables were the pre-scores[*], GPA, gender, and days elapsed between the end of instruction* and the assessment. Because the data were not missing completely at random, we used Multiple Imputation to deal with the missing data (Enders, 2010).

The results in Table 5 show that students in the SUN group achieved significantly higher than Controls on post multiple choice scores (γ_{01} =1.31, p<.001, effect size = 0.55), drawing scores (γ_{01} = 1.19, p< .001, effect size =0.70), and confidence (γ_{01} = 7.37, p< .001, effect size =0.62), controlling for pre-test scores, GPA, gender, and days elapsed (See Table 5 for all the other parameter estimates in the model). (Please insert Table 5) In general, GPA had a positive relationship with the outcome variables and days elapsed had a negative relationship with the outcome variables. Pre-test scores had a significant positive effect only on the post-test scores of multiple choice and confidence. Males had significantly higher scores than females on the multiple choice assessment and more confidence in their responses.

RQ3: Is the impact of SUN Project moderated by students' GPA and gender? Model 2 in Table 4 was used to test these interaction effects. Only GPA significantly moderated the treatment effect on student drawing and multiple choice scores. The treatment effect was greater for students with higher GPA. More specifically, as GPA increased by 1 point, the treatment effect increased by 0.61 on multiple choice and 0.86 on drawing.

RQ4: Do SUN students value their instructional materials more than controls? Students were asked to rate their learning materials in terms of effectiveness on a 0 to 4 point scale. A score of '4' represented 'extremely useful' perceived effectiveness. Individual students' ratings were aggregated at the class level. A one-way ANOVA was conducted to test if there were significant differences in class mean values among SUN, Control, and AP classes. The mean

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[*] The pre-scores for multiple choice questions are based on 15 items.

* End of instruction was defined as end of unit instruction. Teachers were asked not to review before posttest administration at the end of the year.

ratings for SUN, Control, and AP classes were 2.36 (n=19, SD=0.30), 2.11 (n=18, SD=0.26), and 2.41 (n=7, SD=0.33), respectively. There was a significant difference among the means [F(2,41)=4.21, p=0.022]. The Tukey post hoc pairwise comparisons showed that SUN students rated their materials significantly higher than did Controls by 0.26 points (p=0.037).

RQ5 Comparison of SUN and Control vs. non-SUN AP. To better interpret the treatment effect, we further compared SUN and Control with AP students (See Tables 2 and 6) (Please insert Table 6). Controlling for gender, GPA, pre-test scores, and days elapsed, SUN was not significantly different from AP on the MC exam (p=.06) or confidence in responses (p=.44). However, SUN was 1.01 points higher than AP on drawing on average (p<.05). Conversely, the Control group was significantly lower than AP by 1.47 points on the MC exam (p<.05), but not significantly different from AP on the drawing assessment (p=.44) or in confidence (p=.33).

For the drawing assessment, students were asked, ***"Draw what occurs in the mitochondrion during CELLULAR RESPIRATION. Show what happens because of moving electrons. Label your drawing. Explain your drawing in the box below."*** (For a Treatment response please see Figure 1.) (Please insert Figure 1.) Each drawing was graded by three graders with a 19-item rubric of >.90 inter-rater reliability. When examining the percent correct, the difference between the SUN and Control responses is striking (Figure 2) as is the similarity of SUN and AP (Figure 3). (Please insert Figures 2 and 3.) The end product of CR (ATP, item 19) was indicated by only 10% of controls, while 28% of SUN and 41% of the AP group did so. Other items best achieved by the SUN group (Criteria 4, 5 and 10, Figure 2), reflect salient structures in the mitochondrion (pumps and the synthase) and the path of electrons that map to the manipulatives used. As found earlier by Jin and Anderson (2012), none of the groups tracked matter well in terms of reactants and products (Criteria 6 and 7, Figures 2 and 3).

Conclusions:

These results of a cluster, RCT demonstrate that the SUN intervention allows regular biology students to significantly increase their long-term (>2.5 months after instruction on average) conceptual understanding of CR and PS relative to Controls with a moderate effect size of 0.55 on the MC exam and a large effect size of .70 on a drawing assessment. The SUN approach is value added since SUN students either achieved like AP biology students or surpassed them (See Table 6) when significant variables were controlled. Notably the SUN students valued their curricular materials more than Controls. However no group tracked matter well (See Criteria 6 and 7 in Figures 2 and 3). There is a long history of the inability of both teachers and students to learn about biological energy transfer (discussed in Batiza et al., 2013). The SUN approach has broken this pattern for teachers (Batiza et al., 2013) and here shows moderate and large *long-term* effects on student learning. It is interesting that the SUN approach allows students to think about, discuss, and demonstrate mechanism using physical models. Pedagogies that largely depend upon teacher or 'textbook correctness' (Russ et al., 2008) include the failed strategies largely those used by the controls during this study. Although we did not initiate this study with a concern for the treatment of energy across disciplines, it appears that the SUN approach is uniquely positioned to allow for a mechanistic treatment. The SUN tools evoke simplistic but fundamental interactions such as 'like charges repel and opposites attract' to help explain *why* these processes occur. Similar interactions drive some energy transfer processes in chemistry and physics. The fact that fundamental interactions drive energy transfer is one of four concepts *that make it evident that the meaning of energy is equivalent across disciplines.* Therefore this presentation will include reflections on how these unifying concepts could guide development of coherent energy curricula across HS biology, chemistry and physics.

Appendices

Appendix A. References

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Appendix B. Tables and Figures

Table 1. Percent of items within the 20-item SUN Project Student Biological Energy Survey Related to 7 Concept Categories. Bloom's Taxonomy Level is Indicated.

(Consensus of 5 key personnel, all of whom are or have been teachers. Some items span more than one category)

Percent of Measure	Concepts	KNOWLEDGE	COMPREHENSION	APPLICATION	ANALYSIS/ SYNTHESIS/ EVALUATION
12%	**Fundamental laws of matter and energy**		6.25%	2.5%	3.33%
31%	**Cellular respiration (CR)**	10%	11.25%		10%
27%	**Photosynthesis (PS)**	10%	12.5%	2.5%	1.67%
13%	**Comparison of CR and PS**				13.33%
5%	**Comparison of CR to hydrogen fuel cell**		5%		
7%	**Related aspects of biology**			5%	1.67%
5%	**How ATP powers life**				5%
100%	**TOTALS**	20%	35%	10%	35%

Table 2. Means and standard deviations of variables in the SUN, Control, and AP in Year 1

	SUN		Control		AP	
Student level variables	Mean (N=399)	SD	Mean (N=371)	SD	Mean (N=115)	SD
MALE	.46	--	.49	--	.35	--
GPA	2.92	.85	3.08	.74	3.59	.48
MC1	4.88	1.94	4.98	1.80	5.94	2.17
MC2	7.84	2.83	6.64	2.31	9.16	3.37
DR1	.03	.19	.03	.17	.49	1.02
DR2	2.19	3.04	.21	.63	2.03	3.18
CNF1	2.11	.76	2.06	.66	2.44	.70
CNF2	2.96	.72	2.59	.71	2.96	.89
Teacher/class level variables	Mean (N=19)	SD	Mean (N=18)	SD	Mean (N=8)	SD
DAYS Elapsed	84.13	50.05	85.94	62.34	107.88	74.00

Table 3. Correlations among variables in Year 1

	CNF1	CNF2	MC1	MC2	GPA	MALE	SUN	Control	Days elapsed	DR1	DR2
CNF1	1										
CNF2	.438**	1									
MC1	.137**	.136**	1								
MC2	.151**	.355**	.295**	1							
GPA	-.139**	.045	.194**	.244**	1						
MALE	.195**	.163**	.045	.081*	-.189**	1					
SUN	-.027	.186**	-.083*	.109**	-.163**	-.001	1				
Control	-.080*	-.241**	-.032	-.263**	.015	.060	-.770**	1			
Days_elapsed	.073**	-.092*	.034	-.010**	.062	.072*	-.058	-.007	1		
DR1	.204**	.233**	.207**	.316**	.144**	.058	-.123**	-.115**	.133**	1	
DR2	.038	.369**	.121**	.450**	.237**	-.018	.305**	-.378**	-.140**	.287**	1

Notes. MC1=pretest multiple choice, MC2=posttest multiple choice, CNF1=pretest confidence, CNF2=posttest confidence, SUN=SUN treatment, DAYS=days elapsed between instruction and test, DR1=pretest drawing, DR2=posttest drawing; * correlation is significant at the 0.05 level; ** correlation is significant at the 0.01 level.

Table 4. HLM Models

Model 1	Level 1: $Y_{ij} = \beta_{0j} + \beta_1 \Pr e_{ij} + \beta_2 GPA_{ij} + \beta_3 Gender_{ij} + e_{ij}$ Level 2: $\beta_{0j} = \gamma_{00} + \gamma_{01} SUN_j + \gamma_{02} Days\_elapsed_j + U_{0j}$ (Note. For drawing, the slope of GPA was random rather than fixed)
Model 2	Level 1: $Y_{ij} = \beta_{0j} + \beta_{1j} \Pr e_{ij} + \beta_{2j} GPA_{ij} + \beta_{3j} Gender_{ij} + e_{ij}$ Level 2: $\beta_{0j} = \gamma_{00} + \gamma_{01} SUN_j + \gamma_{02} Days\_elapsed_j + U_{0j}$ $\beta_{1j} = \gamma_{10}$ $\beta_{2j} = \gamma_{20} + \gamma_{21} SUN_j + U_{2j}$ $\beta_{3j} = \gamma_{30} + \gamma_{31} SUN_j + U_{3j}$

Table 5. Parameter estimates for treatment effects (Model 1) and moderation effects (Model 2) of SUN vs. Control in Year 1

Note. N=770. Standard errors were reported in the parentheses. ** indicates significance at .01 level and * indicates significance at .05 level.

	DV: Multiple Choice		DV: Drawing		DV: Confidence	
Parameters	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Fixed Effects						
Intercept	6.85 (0.29)**	6.88 (0.30)**	0.93 (0.29)**	1.06 (0.32)**	2.81 (0.10)**	2.78 (0.10)**
Pre-test	0.26 (0.05)**	0.26 (0.05)**	0.73 (0.51)	0.78 (0.50)	0.43 (0.03)**	0.43 (0.04)**
GPA	0.72 (0.14)**	0.38 (0.18)*	0.75 (0.16)**	0.29 (0.10)**	0.13 (0.03)**	0.07 (0.05)
Male	0.64 (0.19)**	0.52 (0.23)*	0.15 (0.14)	0.04 (0.11)	0.11 (0.05)*	0.13 (0.06)*
Days Elapsed	-0.007 (0.003)**	-0.006 (0.003)*	-0.006 (0.003)	-0.010 (0.003)**	-0.003 (0.001)**	-0.003 (0.001)**
SUN	1.31 (0.23)**	1.21 (0.30)**	1.19 (0.44)**	1.81 (0.37)**	0.37 (0.08)**	0.38 (0.10)**
GPA*SUN	--	0.61 (0.26)*	--	0.86 (0.26)**	--	0.09 (0.07)

Male*SUN	--	0.19 (0.37)	--	0.15 (0.26)	--	-0.04 (0.10)
Random Effects						
Intercept	0.20 (0.12)	0.22 (0.12)	1.14 (0.36)**	0.91 (0.28)**	0.03 (0.01)*	0.03 (0.01)*
GPA	--	0.07(0.12)	0.55 (0.44)	0.43 (0.25)	--	0.00 (0.04)
MALE	--	0.03(0.16)	--	0.02 (0.24)	--	0.00 (0.05)
GPA with Intercept	--	--	0.66 (0.33)*	--		
Residual	5.63 (0.33)**	5.51 (0.33) **	2.91 (0.57)**	2.89 (0.55)**	0.35 (0.02)**	0.35 (0.02)**

Table 6. Parameter estimates for the comparison of SUN and Control vs. AP in Year 1
Note. N=885. Standard errors were reported in the parentheses. ** indicates significance at .01 level and * indicates significance at .05 level.

	DV: Multiple Choice	DV: Drawing	DV: Confidence
Fixed Effects			
Intercept	8.27 (0.66)**	1.30 (0.48)**	2.87 (0.02)**
Pre-test	0.30 (0.05)**	1.05 (0.30)**	0.45 (0.03)**
GPA	0.79 (0.15)**	0.84 (0.18)**	0.14 (0.03)**
Male	0.76 (0.19)**	0.18 (0.14)	0.16 (0.05)**
Days Elapsed	-0.004 (0.003)	-0.005 (0.003)	-0.002 (0.001)
SUN	-0.40 (0.64)	1.01 (0.52)*	0.18 (0.21)
Control	-1.47 (0.62)*	-0.33 (0.42)	-0.20 (020)
Random Effects			
Intercept	0.56 (0.23)*	1.18 (0.34)**	0.07 (0.02) **
GPA	0.38 (0.27)	0.72 (0.57)	--
GPA with Intercept	0.38 (0.18)*	0.73 (0.30)*	--
Residual	5.53 (0.30)**	3.06 (0.51)**	0.35 (0.02)**

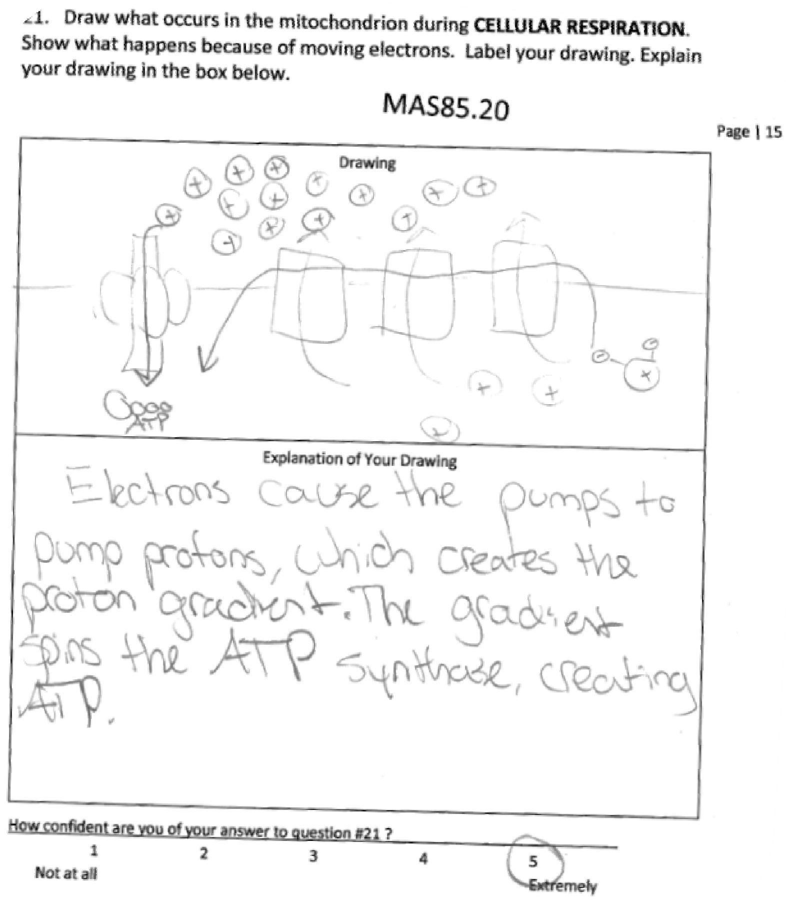

Figure 1. A. Above is the "post" drawing of a regular biology male student in the Treatment Group with a 3.9 previous GPA, 117 days after instruction. This student exhibits mechanistic thinking in terms of the three interacting systems that allow for energy transfer in the mitochondrion: 1) the movement of electrons which causes 2) the pumping of protons, which in turn powers 3) the production of ATP by the ATP synthase. However, the role of reactants (food + oxygen, which are the electron donor and acceptor) and the products made when electrons move (carbon dioxide + water) are not referenced. Notice that he is "extremely" confident regarding this response.

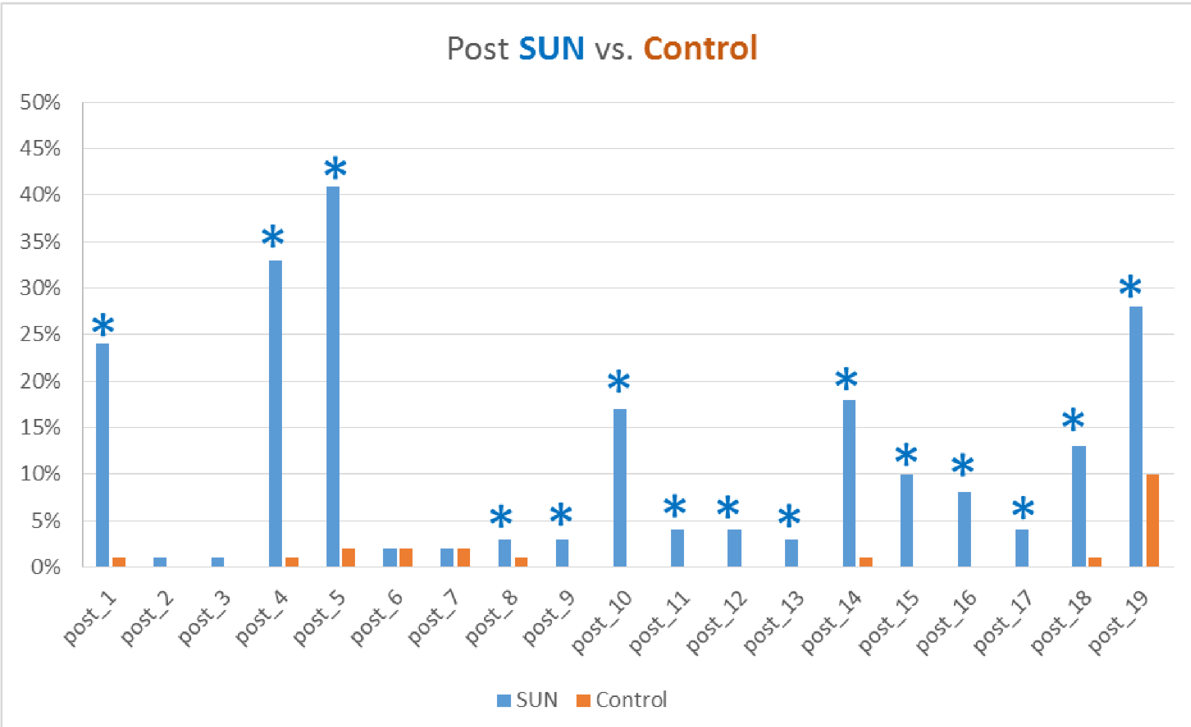

Figure 2. Comparison of percentage of SUN (blue) and Control (orange) students achieving the 'drawing with written explanation' criteria on the post assessment >2.5 months after instruction. No adjustments were made for control of variables. N = 388 SUN and 361 Control students. Significant differences (p=.00 or.01) between SUN and Control are shown with asterisks (blue where SUN is greater). This assessment was developed to include concepts from: 1. General lower level criteria regarding structures and their spatial relationships (items 1 – 5); 2.The process of cellular respiration (items 6-13); 4.The production of ATP (items 14 – 17), and 4.Energy transformations (items 18 and 19).

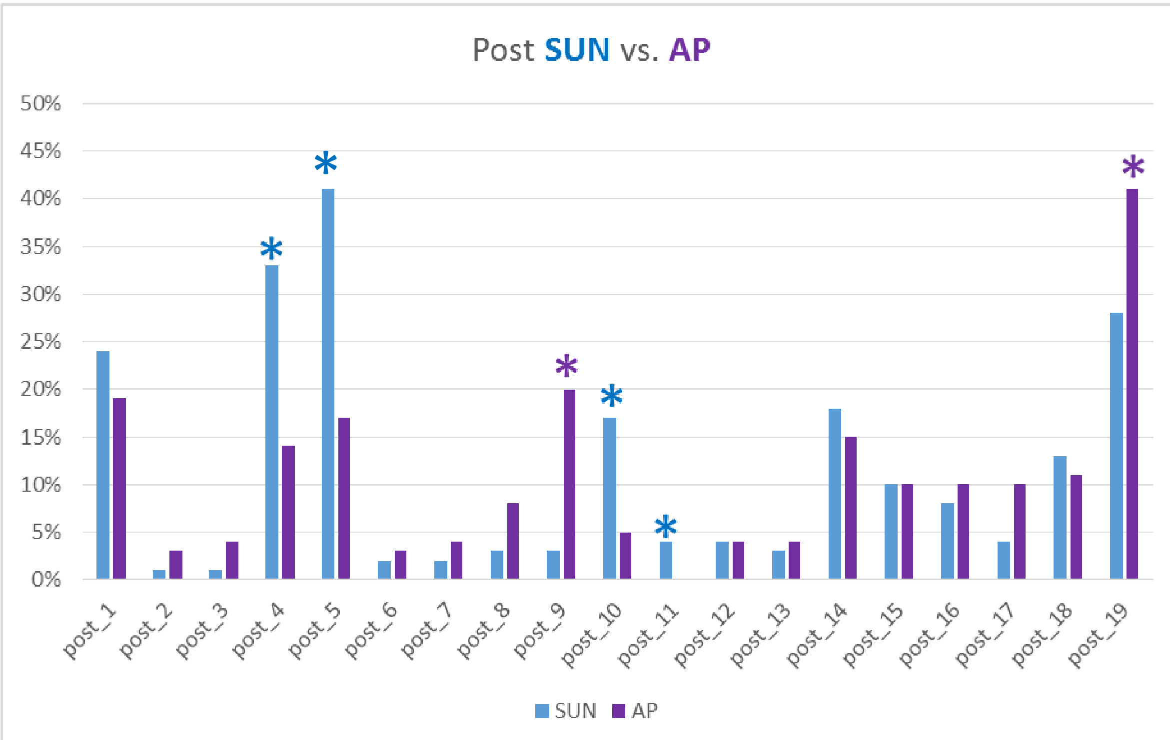

Figure 3. Comparison of percentage of SUN (blue) and AP (purple) students achieving drawing with explanation criteria >2.5 months after instruction. No adjustments were made for control of variables. N=388 SUN and 106 AP students. Significant differences (p=.00 or .01) between SUN and AP are shown with asterisks. Those that favor SUN are blue and those that favor the AP group are purple. This assessment was developed by the project to include concepts from four broad categories: 1. General lower level criteria regarding structures and their spatial relationships (items 1 – 5); 2.The process of cellular respiration (items 6-13); 4.The production of ATP (items 14 – 17), and 4.Energy transformations (items 18 and 19).