

Supplemental Material

CBE—Life Sciences Education

Angra *et al.*

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Appendix A: Graph rubric citation broken down by source and category

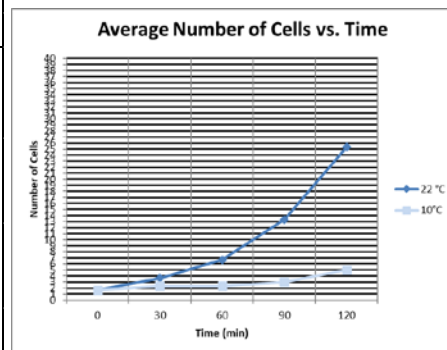
Graph Rubric Elements	Sources that Informed Descriptions
<p>Descriptive title</p> <p>a) in the form of a statement</p> <p>b) mention the subject</p> <p>c) appropriate variables</p> <p>d) include relevant details about the experiment that help understand the take home message.</p>	<p>Kosslyn, 1994; Evergreen, 2018</p> <p><u>Angra & Gardner, 2017</u></p> <p><u>Angra & Gardner, 2017</u></p> <p><i>Puhan et al. 2006; Angra & Gardner, 2017</i></p>
<p>Label for the X axis (e.g. time)</p> <p>a) appropriate and descriptive for the experiment.</p> <p>b) graphs with categorical independent variables should have a label under each set of data and a larger label under all data plotted.</p>	<p>Kosslyn, 1994; Few, 2004; Federico et al., 2012</p> <p><i>Puhan et al. 2006; Angra & Gardner, 2017</i></p> <p><i>Elliot et al., 2006; Puhan et al. 2006; Angra & Gardner, 2017</i></p>
<p>Label for the Y axis (e.g. heart rate)</p> <p>• Should be appropriate and descriptive for the experiment. If the data is manipulated (average, change, percentage, etc.), then it should be indicated on the y axis.</p>	<p>Kosslyn, 1994; Few, 2004; Federico et al., 2012</p> <p><i>Elliot et al., 2006; Puhan et al. 2006; Angra & Gardner, 2017</i></p>
<p>Units for the X axis (e.g. seconds)</p> <p>• Should be appropriate and descriptive for the data displayed.</p>	<p><i>Leinhardt et al., 1990; Puhan et al. 2006</i></p>
<p>Units for the Y axis (e.g. average beats per minute)</p> <p>• Should be appropriate and descriptive for the data displayed.</p>	<p><i>Leinhardt et al., 1990; Puhan et al. 2006</i></p>
<p>Scale (appropriate intervals and range for data)</p> <p>a) Increments are clear and without clutter</p> <p>b) appropriate significant figures.</p> <p>c) If the scale is discontinuous or doesn't start at the origin, it should be indicated by a break in the axis.</p>	<p><i>Cleveland, 1994</i></p> <p>Tufte, 1983; Leinhardt et al., 1990; Kosslyn, 1994; Few, 2004; Duke et al., 2015; Evergreen, 2018</p> <p>Evergreen, 2018</p> <p>Kosslyn, 1994; Duke et al., 2015</p>
<p>Key (defines different data sets that are plotted)</p> <p>a) descriptions of different colors (if applicable)</p> <p>b) the sample size</p> <p>c) the number of trials.</p>	<p>Few, 2004; Evergreen, 2018</p> <p><u>Angra & Gardner, 2017</u></p> <p><u>Angra & Gardner, 2017</u></p>
<p>Ease of Understanding-Aesthetics</p> <p>a) the data plotted takes up sufficient room in the Cartesian plane</p> <p>b) makes use of legible size font</p> <p>c) the x and y axis lines are clear and legible</p> <p>d) the graph displays data in an appropriate number of bars and lines (maximize data-ink ratio)</p> <p>e) is devoid of chart junk elements such as: distracting background colors, patterns, and dark gridlines</p>	<p>Tufte, 1983</p> <p>Kosslyn, 1994; Stengel et al., 2008; Duke et al., 2015; Evergreen, 2018</p> <p><i>Duke et al., 2015; Evergreen, 2018</i></p> <p>Tufte, 1983; Kosslyn, 1994; Puhan et al. 2006; Duke et al., 2015</p> <p>Tufte, 1983; Cooper et al., 2003; Puhan et al. 2006; Stengel et al., 2008; Federico et al., 2012; Evergreen, 2014; Rougier et al., 2014; Duke et al., 2015; Evergreen, 2018</p>
<p>Ease of Understanding-Take home message</p> <p>a) If the graph has sound construction and mechanics that allow for clear sorting of trends.</p> <p>b) Easy to formulate a take home message.</p>	<p><i>Cooper et al., 2003; Rougier et al., 2014; Evergreen, 2018</i></p> <p><i>Cooper et al., 2003; Federico et al., 2012; Rougier et al., 2014; Duke et al., 2015; Evergreen, 2018</i></p>
<p>Graph Type (Bar, line, scatter, dot, box and whisker)</p> <p>Data displayed in a graph is appropriate for both independent and dependent experimental variables (i.e. categorical and continuous) and data. (*Referring to the data form)</p>	<p><i>Padilla et al., 1986; Cleveland, 1994; Kosslyn, 1994; Schriger & Cooper, 2001; Few, 2004; Leonard & Patterson, 2004; Patterson & Leonard, 2005; Drummond et al., 2011; Franzblau & Chung, 2012; Humphrey et al., 2013; Duke et al., 2015; Saxon, 2015; Weissgerber et al., 2015; Klaus, 2016; Evergreen, 2018; Angra & Gardner, 2016; Angra & Gardner, 2017</i></p>
<p>Data Displayed (Raw, Averages, Changes, Percentage)</p> <p>If the graph indicates the type of data (ex. Raw, averages, etc.) that are plotted. There should be a clear distinction between raw data and manipulated data based on the information presented in the key (ie. sample size and number of trials) and axis label. If the graph is showing averages, then it should also be accompanied with STDEV or error bars.</p>	<p><i>Wild and Pfannkuch, 1999; Friel & Bright, 1996; Konold & Higgins, 2003; Konold et al., 2015</i></p>
<p>*Alignment* (at least one of the graphs presented should align with the research question and hypothesis. Other graphs can be exploratory.)</p> <p>If the graph is completely aligned with the research question and/or hypothesis. In other words, the independent, dependent variables, and information about the experiment are explicit.</p>	<p><i>Konold & Higgins, 2003; Rougier et al., 2014</i></p> <p><u>Angra & Gardner, 2016; Angra & Gardner, 2017</u></p>

Appendix B: Completed rubric for a sample graph from the rubric training materials for the external stage. Complete version is available upon request by the corresponding author.

Research Question:	Does temperature affect the growth rate of this type of bacteria?
Hypothesis:	The bacteria will have different growth rates at different temperatures.

	ID of graph or set of graphs:	Excellent (2)	Present but Needs Improvement (1)	Absent/Inappropriate (0)
Graph Mechanics	Descriptive title P/A- Should be: a) in the form of a statement, b) mention the subject, c) appropriate variables, and d) include relevant details about the experiment that help understand the take home message. NI- If the title is missing any one of the four points mentioned above.		Needs to be in a statement, mention the subject (bacteria), and include details about the experiment (temperatures)	
	Label for the X axis (e.g. time) P/A- Should be appropriate and descriptive for the experiment. For graphs with categorical independent variables, there needs to be a label under each set of data and a larger label under all data plotted. NI- If the label is missing any one of the points mentioned above.	x		
	Label for the Y axis (e.g. heart rate) P/A- Should be appropriate and descriptive for the experiment. If the data is manipulated (average, change, percentage, etc.), then it should be indicated on the y axis. NI- If the label is missing any one of the points mentioned above.		Should say "Average Number of Cells", since that is the data plotted.	
	Units for the X axis (e.g. seconds) P/A- Should be appropriate and descriptive for the data displayed. NI- If the units are not appropriate or descriptive.	x		
	Units for the Y axis (e.g. average beats per minute) P/A- Should be appropriate and descriptive for the data displayed. NI- If the units are not appropriate or descriptive.	x		
	Scale (appropriate intervals and range for data) P/A- Should be appropriate for the data displayed such that the increments are clear and without clutter and includes appropriate significant figures. If the scale is discontinuous or doesn't start at the origin, it should be indicated by a break in the axis. NI- If the scale is not appropriate for the data such that it is cluttered, does not include appropriate significant figures, and/or if the scale does not indicate axis break.		The y axis can be re-scaled so that it goes from -2 to 26 and a proper increment should be chosen so that numbers do not clutter the y axis.	
	Key (defines different data sets that are plotted) P/A- Should be appropriate and descriptive for the data displayed. It should include: a) descriptions of different colors (if applicable), b) the sample size and c) the number of trials. NI- If the key is not descriptive and does not indicate the sample size.		Since the graph is showing averages, a key showing the sample size for each temperature is necessary.	

	Excellent (2)	Present but Needs Improvement (1)	Absent/Inappropriate (0)
<p>Communication</p> <p>Ease of Understanding-Aesthetics E- If the graph is aesthetically pleasing, meaning that: a) the data plotted takes up sufficient room in the Cartesian plane, b) makes use of legible size font, c) the x and y axis lines are clear and legible, d) the graph displays data in an appropriate number of bars and lines, and e) is devoid of chart junk elements such as: distracting background colors, patterns, and dark gridlines NI- If the graph has one of the following flaws: a) the graph displays too much white space, b) the font size is too small, c) the x and y axis lines are not clear and legible, d) the graph shows too many bars or lines OR e) elements of chart junk are clouding interpretation of data. U- If the graph has multiple flaws, which interfere with the understanding and interpretation of data.</p> <p>Ease of Understanding-Take home message E- If the graph has sound construction and mechanics that allow for clear sorting of trends and take home message. NI- If data trends are difficult to observe or it is difficult to formulate a proper take home message. U- If the graph is ineffective at communicating data trends and take home message, such that it causes confusion.</p>			<p>This graph has multiple flaws: the gridlines are distracting, there is unnecessary white space above the data lines, and the two data lines are similar in color. Overall, there is a lot of chartjunk in this graph</p>
<p>Graph Choice</p> <p>Graph Type (Bar, line, scatter, dot, box and whisker) E- If data displayed in a graph is appropriate for both independent and dependent experimental variables (i.e. categorical and continuous) and data. (*Referring to the data form) NI- If data displayed in a graph is a) not suitable for either the dependent or independent experimental variables OR b) there is a better way to present data. U- If the graph type is not suitable for both experimental variables.</p> <p>Data Displayed (Raw, Averages, Changes, Percentage) E- If the graph indicates the type of data (ex. Raw, averages, etc.) that are plotted. There should be a clear distinction between raw data and manipulated data based on the information presented in the key (ie. sample size and number of trials) and axis label. If the graph is showing averages, then it should also be accompanied with STDEV or error bars. NI- If the graph is missing one of points mentioned above. U- If data type is inappropriate for the graph type</p> <p>*Alignment* (at least one of the graphs presented should align with the research question and hypothesis. Other graphs can be exploratory.) E- If the graph is completely aligned with the research question and/or hypothesis. In other words, the independent, dependent variables, and information about the experiment are explicit. NI- If the graph is partially aligned with the research question and/or hypothesis. In other words, the graph is missing information about either the independent, dependent, or details about the experiment. U- If the graph is not aligned with the research question and/or hypothesis.</p>		<p>Although it is easy to note the trends in this graph, it is difficult to formulate an accurate take home message since the subject, bacteria is not mentioned in the graph.</p> <p>Since the graph is showing averages, the data points need to be accompanied with error bars.</p> <p>The graph is partially aligned with the research question and hypothesis because it does not display information on the subjects.</p>	

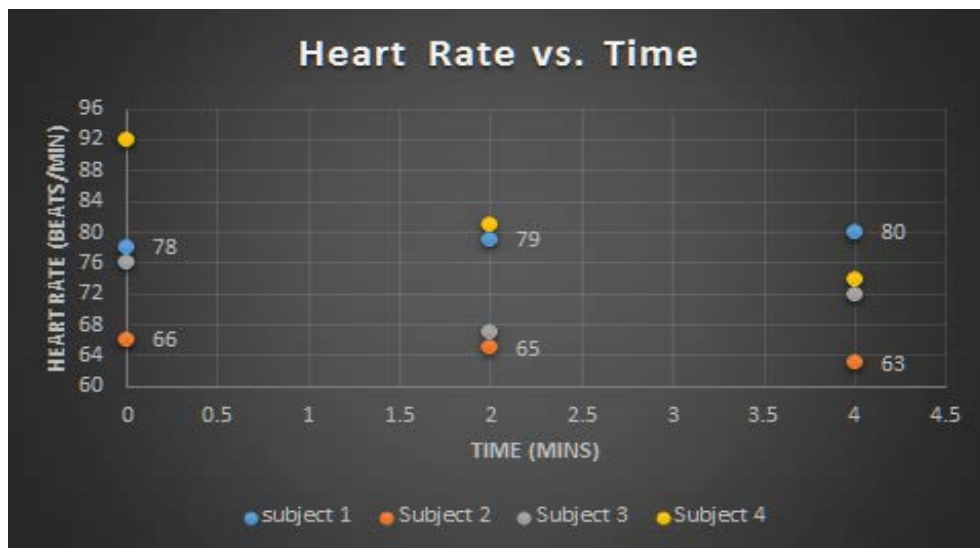


Appendix C: Graphs used during the structural stages by science education researchers and graduate students

GRAPH 1

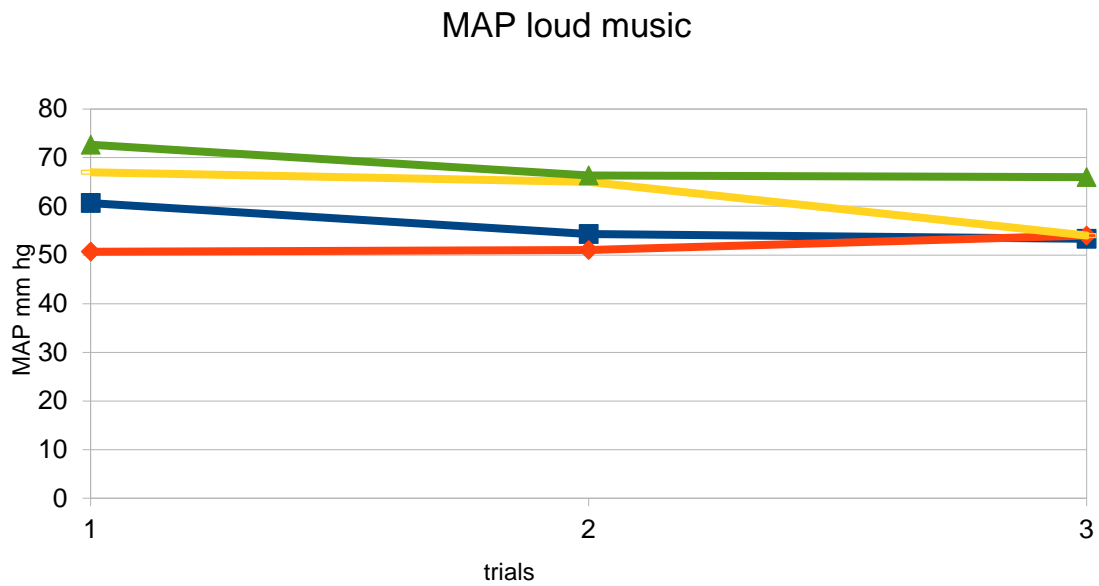
The scatter and line graphs below were used only by the science education researchers during the first round of the structural stage for feedback:

- **Question:** Do different genres of music affect an individual's heart rate?
- **Hypothesis:** Music genres do affect a person's heart rate differently.



GRAPH 2

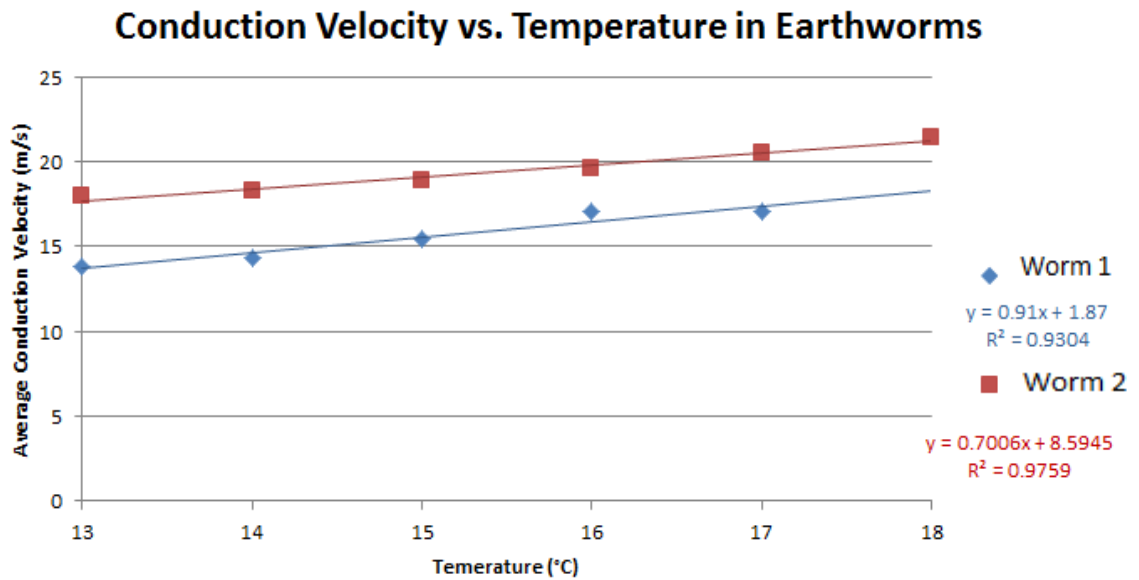
Question: Does listening to music increase or decrease the HR and MAP depending on the genre?
Hypothesis: Slower music will decrease the HR below normal levels whereas listening to upbeat/faster music will increase the HR



GRAPH 3

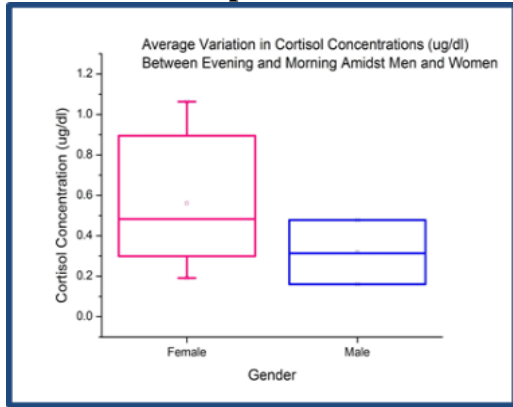
The graph below was used by both science education researchers and graduate students during the second round of the structural stage.

- **Question:** How does the conduction velocity in the median giant axon alter with a change in temperature?
- **Hypothesis:** We hypothesize temperature affects the conduction velocity of the median giant axon.

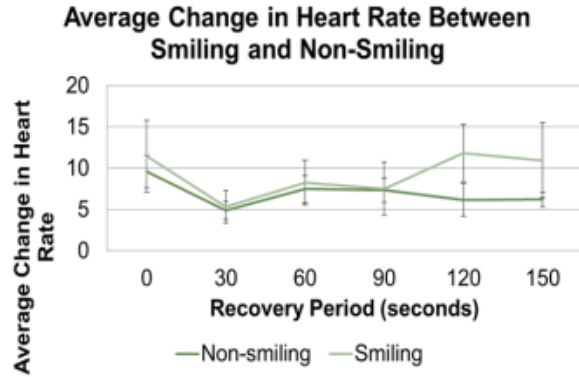


Appendix D: Graphs critiqued by undergraduate students during the external stage.

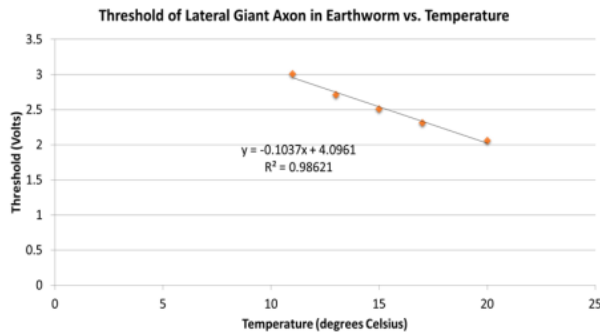
Graph 1



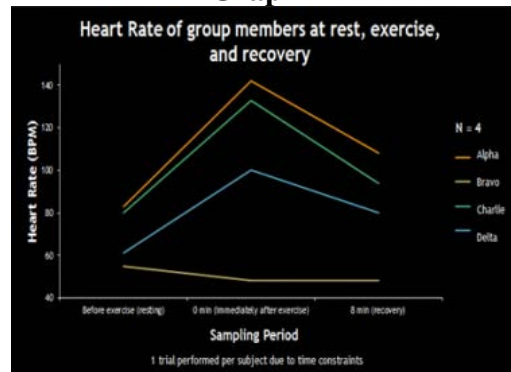
Graph 2



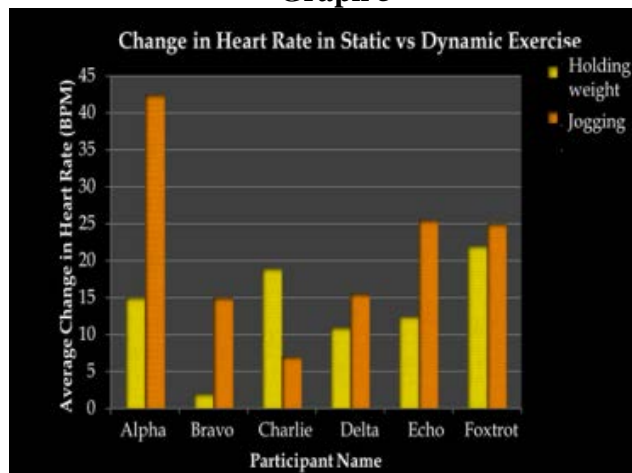
Graph 3



Graph 4



Graph 5



Appendix E- Descriptions of graphs critiqued by students and professors

Table E.1- Descriptions of graphs critiqued by undergraduate students who were students in a physiology laboratory, where they had repeated practice with the graph rubric during the Spring 2015 semester. *These are descriptions of graphs in Appendix D.*

	Graph #	1	2	3	4	5
Graph Descriptions	Type	Box and whisker	Line	Scatter	Line	Double bar
	Context-Physiology Topic Lab	Cortisol	Cardiovascular	Action potentials	Cardiovascular	Student's choice
	Other Descriptors	Cortisol concentration, two categories plotted.	Average change in heart rate between smiling and non-smiling; mean +/- SEM	Decreasing slope; lots of white space on the graph	Black background with 4 smooth lines of a different color	Black background; paired bars showing mean but no +/- SEM

Table E.2- Descriptions of student constructed graphs that were critiqued by Instructor 1 who taught an upper-level field ecology course and a freshman-level Course-Based Undergraduate Research Experience (CURE).

	Graph #	1	2	3	4	5	6	7	8
Graph Descriptions	Type	Bar	Scatter	Bar	Scatter	Bar	Bar	Stacked bar	Bar
	Context	Field Ecology	Field Ecology	Field Ecology	Field Ecology	Field Ecology	Field Ecology	CURE	CURE
	Other descriptors	Five treatments; percentage of measured variable	Scatter with linear regression	Two categories; Average +/- error bar	Scatter with linear regression	Three sampling days; Proportion of measured variable	Paired bar graph; average w/ error bar	Two treatments; two categories (% for each)	Four treatments; Average +/- error bar

Table E.3- Descriptions of student constructed graphs that were critiqued by Instructor 2 who taught a sophomore-level cell biology and neurobiology.

	Graph #	1-5	6	7	8	9	10
Graph Descriptions	Type	Line	Line and symbol	Paired bars	Line and symbol	Bar	Box and whisker
	Context	Cell Biology	Neurobiology	Neurobiology	Neurobiology	Neurobiology	Neurobiology
	Other descriptors	Exam question graph sketches; Bond energies to determine DNA form	Four conditions	Treatment and control for eight trials	Baseline and treatment	Three conditions to compare	Before, during, and after treatment

Table E.4- Descriptions of student constructed graphs that were critiqued by Instructor 3 who taught an upper-level conservation biology course.

	Graph #	1	2	3	4	5
Graph Descriptions	Type	Line	Scatter	Scatter	Line and symbol	Bar
	Context	Conservation biology	Conservation biology	Conservation biology	Conservation biology	Conservation biology
	Other descriptors	Raw simulation output for 100 runs	Average +/- error bars for three simulated conditions (100 iterations over 200 years)	Average +/- error bars for four independent variable values	Average +/- error bars for three different conditions	Average +/- error bars for four different conditions

Table E.5a- Descriptions of student constructed graphs that were critiqued by Instructor 4 in the neurophysiology context.

	Graph #	1	2	3	4
Graph Descriptions	Type	Scatter	Scatter	Scatter	Scatter
	Context	Neurophysiology	Neurophysiology	Neurophysiology	Neurophysiology
	Other descriptors	Scatter with regression line	Measurements from two subjects	Measurements from two subjects	Measurements from two subjects

Table E.5b- Descriptions of student constructed graphs that were critiqued by Instructor 4 in the endocrine physiology context.

	Graph #	1	2	3	4
Graph Descriptions	Type	Line and symbol	Bars	Scatter	Box and whisker
	Context	Endocrine physiology	Endocrine physiology	Endocrine physiology	Endocrine physiology
	Other descriptors	Two conditions over time	One measured variable at six time points	Scatter with regression line	Four conditions

Table E.5c- Descriptions of student constructed graphs that were critiqued by Instructor 4 in the cardiovascular physiology context.

		G1	G2	G3	G4
Graph Descriptions	Type	Line and symbol	Line	Paired bars	Scatter
	Context	Cardiovascular physiology	Cardiovascular physiology	Cardiovascular physiology	Cardiovascular physiology
	Other descriptors	Data for four subjects at three time points; plotted separately	Two treatments with three trial points	Three sets of paired bars (change for three measured variables) with two treatment conditions each	Scatter with regression line

Appendix F- Detailed IRR agreement between biology instructors and expert rater

* average from the overall rubric scoring across graphs for each instructor

n = number of graphs evaluated

	Graph Rubric Category	Instructor 1 (n = 8)	Instructor 2 (n = 10)	Instructor 3 (n=5)	Instructor 4 (n =12)
Graph Mechanics	Descriptive Title	100	70	60	83
	Label for the X axis	100	70	40	100
	Label for the Y axis	62.5	80	100	67
	Units for the X axis	75	100	100	75
	Units for the Y axis	62.5	100	60	92
	Scale	100	60	80	83
	Key	100	30	60	83
Communication	Ease of Understanding- Aesthetics	75	50	40	67
	Ease of Understanding- Take home message	75	90	100	67
Graph Choice	Graph Type	100	90	80	67
	Data Displayed	62.5	80	60	67
	Alignment	87.5	70	80	83
	Average (%) Task Interrater Reliability*	83 ± 9	74 ± 4	72 ±15	78 ± 7

Appendix G: Table of citations of graphs from introductory biology textbooks during the external stage

Textbook	Randomly Selected Chapters	Number of Pages Analyzed	Number of Graphs Analyzed	Graphs Randomly Selected for IRR agreement
Campbell et al., 2011	1, 2, 5, 9, 10, 15, 22, 23, 26, 29	n/a online textbook	204 graphs present, but analyzed 40 graphs (20%)	Chapter 1, graph 1.21 Chapter 2, graph 2.19 Chapter 5, left graph 5.9 Chapter 9, top graph 9.22 Chapter 10, graph 10.2 Chapter 15, middle graph in panel A 15.11 Chapter 22, graph 22.7 Chapter 29, graph 29.14
Raven et al., 2008	20, 23, 25, 28, 34, 44, 45, 52, 58, 59	203	43	Chapter 20, graph 20.1 Chapter 20, bottom graph 20.13 Chapter 20, graph 20.16 Chapter 23, graph 23.12 Chapter 44, graph 44.8 Chapter 45, graph 45.18 Chapter 58, graph 58.8 Chapter 59, graph 59.4 Chapter 59, graph 59.15
Sadava et al., 2009	5, 11, 14, 28, 38, 45, 52, 53, 56, 57	207	35	Chapter 28, <i>Investigating Life</i> top graph 28.9 Chapter 45, <i>Tools for Investigating Life</i> graph 45.8 Chapter 45, graph 45.11 Chapter 45, graph 45.15 Chapter 45, graph 45.17 Chapter 52, <i>Investigating Life</i> graph 52.17 Chapter 57, graph 57.9a
Singh-Cundy & Shin, 2015	2, 3, 19, 20, 22, 26, 27, 29, 30, 33	227	17	Chapter 20, graph 20.3a Chapter 26, <i>Biology Matters</i> bottom graph Chapter 29, top graph 29.9
Urry et al., 2014	3, 4, 6, 11, 13, 18, 22, 29, 32, 38	211	18	Chapter 6, graph 6.6 Chapter 6, graph 6.16 Chapter 38, <i>Scientific Skills</i> graph

1. Campbell, A., Heyer, L., Paradise, C., Sellers, P., & Barsoum, M. (2011, January). Integrating Concepts in Biology for Introductory College Biology. In *Molecular Biology of the Cell* (Vol. 22). 8120 Woodmont Ave, Ste 750, Bethesda, MD 20814-2755 USA: Amer Soc Cell Biology.
2. Raven, P. H., Johnson, G. B., Losos, J. B., Mason, K. A. & Singer, S. R. (2008): *Biology*, 8th ed.; Boston (McGraw-Hill).
3. Sadava, D. E., Hillis, D. M., Heller, H. C., & Berenbaum, M. (2009). *Life: the science of biology* (Vol. 2). Macmillan.
4. Singh-Cundy, A., Shin, G. (2010). *Discover biology* (6th Edition). Sinauer Associates, Inc.
5. Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P. V., Jackson, R. B., & Reece, J. B. (2014). *Campbell biology in focus*. Pearson.

Appendix H: Detailed Version of Textbook Analysis using the Graph Rubric.

	Graph Rubric Category	Textbooks	Present/Appropriate	Needs Improvement	Unsatisfactory
Graph Mechanics	Descriptive Title	Singh-Cundy & Shin, 2015	83	0	17
		Urry et al., 2014	33	60	7
		Sadava et al., 2009	89	11	0
		Raven et al., 2008	90	10	0
		Campbell et al., 2011	65	35	0
	Label for the X axis	Singh-Cundy & Shin, 2015	92	8	0
		Urry et al., 2014	87	13	0
		Sadava et al., 2009	83	8	9
		Raven et al., 2008	74	10	16
		Campbell et al., 2011	62	26	12
	Label for the Y axis	Singh-Cundy & Shin, 2015	84	8	8
		Urry et al., 2014	100	0	0
		Sadava et al., 2009	94	3	3
		Raven et al., 2008	95	5	0
		Campbell et al., 2011	64	36	0
	Units for the X axis	Singh-Cundy & Shin, 2015	92	0	8
		Urry et al., 2014	67	0	33
		Sadava et al., 2009	75	0	25
		Raven et al., 2008	88	0	12
		Campbell et al., 2011	97	0	3
	Units for the Y axis	Singh-Cundy & Shin, 2015	50	0	50
		Urry et al., 2014	60	0	40
		Sadava et al., 2009	72	0	28
		Raven et al., 2008	93	0	7
		Campbell et al., 2011	85	0	15

Appendix H: Detailed Version of Textbook Analysis using the Graph Rubric.

	Scale	Singh-Cundy & Shin, 2015	33	25	42
		Urry et al., 2014	27	46	27
		Sadava et al., 2009	42	42	16
		Raven et al., 2008	52	48	0
		Campbell et al., 2011	91	9	0
	Key	Singh-Cundy & Shin, 2015	55	45	0
		Urry et al., 2014	53	47	0
		Sadava et al., 2009	69	31	0
		Raven et al., 2008	38	62	0
		Campbell et al., 2011	23	77	0
Communication	Ease of Understanding- Aesthetics	Singh-Cundy & Shin, 2015	42	58	0
		Urry et al., 2014	67	33	0
		Sadava et al., 2009	72	28	0
		Raven et al., 2008	74	26	0
		Campbell et al., 2011	88	12	0
	Ease of Understanding- Take home message	Singh-Cundy & Shin, 2015	42	58	0
		Urry et al., 2014	93	7	0
		Sadava et al., 2009	97	3	0
		Raven et al., 2008	95	5	0
		Campbell et al., 2011	88	12	0
Graph Choice	Graph Type	Singh-Cundy & Shin, 2015	75	25	0
		Urry et al., 2014	93	7	0
		Sadava et al., 2009	86	14	0
		Raven et al., 2008	71	29	0
		Campbell et al., 2011	88	12	0
	Data Displayed	Singh-Cundy & Shin, 2015	50	50	0

Appendix H: Detailed Version of Textbook Analysis using the Graph Rubric.

		Urry et al., 2014	27	73	0
		Sadava et al., 2009	75	25	0
		Raven et al., 2008	74	26	0
		Campbell et al., 2011	77	23	0
	Alignment	Singh-Cundy & Shin, 2015			
		Urry et al., 2014			
		Sadava et al., 2009			
		Raven et al., 2008			
		Campbell et al., 2011			