Supporting Information for

Assessing Differences Between Three Virtual General Chemistry Experiments and Similar Hands-On Experiments

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Interview Protocol:

1) I first wanted to just remind you of who I am and what my dissertation project is on. I am Cory Hensen and I am currently working on my Ph.D. under Jack Barbera. My dissertation project is looking at the efficacy of virtual laboratories. We are currently starting year 1 of the preliminary data collection before we move on to starting with students, we want to first understand where faculty are coming from through these interviews. Before I can begin looking at virtual laboratories, I first want to understand the learning objectives for the specific experiments I am interested in. Currently you are teaching (coordinating) Chem [course number] which covers the [experiment name] experiment in which I am interested.
    a. If you are okay with being interviewed, I would like to go over the informed consent [informed consent details].
    b. Thank you for signing that form. I am now going to turn on the audio recorder if you are okay with that.
2) I first want to start with asking how long you have been a faculty member at this institution?
3) How many of those years have you been involved in the general chemistry laboratory?
    a. In what capacity are you involved in the general chemistry laboratory?
4) Now I wanted to get into asking about a specific laboratory experiment. This term the students are doing an experiment over [topic]. Here is a copy of the procedure in case you need it. I wanted to ask you what learning objectives, or things you want your students to get out of this lab, you have?
    a. How many of these are assessed?
    b. If students missed today’s experiment, what would they miss out on?

Table SI1: Demographics

		Beer's Law	*Calorimetry*	*Titration*
Total Enrollment (N)		630	484	355
Consented (N)	Hands-on	174	129	72
	Virtual	216	152	117
**Female (%)*	Hands-on	61.5	55.0	56.0
	Virtual	55.0	57.2	65.8
**White (%)*	Hands-on	57.5	49.6	44.0
	Virtual	49.1	57.2	49.6
**Biology Major (%)*	Hands-on	36.2	40.3	41.3
	Virtual	25.9	35.5	42.7

*****These categories represent the plurality for all experiments and sections for both the consented and overall course populations

Table SI2: List of overarching learning goals and experiment-specific learning objectives by faculty member

Faculty	**Overarching Goals**	**Beer's Law Objectives**	**Calorimetry Objectives**	**Titration Objectives**
	After completing this course, students will be able to do:	After doing this experiment, students will be able to:		
A	o Graphical analysis	o Understand and use the relationship between absorbance and concentration o Prepare solutions from both a stock solution and a solid o Calculate the molarity of a given solution	o Experimentally determine and feel enthalpy changes o Use Hess's Law to predict the enthalpy change for a given reaction o Understand the relationship between energy and enthalpy at a constant pressure o Understand the relationship between energy and temperature	o Successfully preform a titration o Identify key points on a titration curve o Use a pH titration curve to determine the concentration of a solution containing an acid o Identify the Brønsted-Lowry acids and bases present in solution and which of these substance(s) control the pH
B	o Error analysis o Measurement	o Visualize concentration strength in a serial dilution o Derive graphically the relationship between absorbance and concentration o Use the relationship between absorbance and concentration to solve for an unknown concentration	o Experimentally determine the thermal energy (q) for a given reaction o Use thermal energy to calculate the enthalpy change of a given reaction o Describe the relationship between a measured temperature change and an enthalpy change	o Visually identify a change in pH during a titration o Use a titration curve to identify the molar mass and pKa of an unknown analyte
C	o Comparison with literature values o Unit analysis	o Graphically determine the relationship between absorbance and concentration o Determine an unknown concentration using the relationship between absorbance and concentration o Successfully prepare a calibration curve o Prepare standard solutions from a stock solution	o Experimentally determine the enthalpy of neutralization of phosphoric acid o Compare the experimental value with the literature value and determine percent error o Apply and understand the first law of thermodynamics	o Identify key points on a titration curve o Determine the pKa and molar mass of an unknown analyte using a titration curve o Visualize pH changes using a mixture of indicators

D	Graphing Collaboration	Determine graphically the relationship between absorbance and concentration Use the relationship to solve for an unknown concentration Understand how light interacts with matter to produce the maximum wavelength Understand real-world applications of spectroscopy	Experimentally determine the enthalpy of dissolution Predict the sign of the change in enthalpy from a temperature change Calculate heat energy by using a temperature change Relate enthalpy changes to bond formation	Determine the pKa and identify of an unknown acid using a titration curve Predict the pH at the equivalence point Identify key points on a titration curve Predict which acid-base species are present at various points throughout a titration
E	Graphing	Prepare calibration standard solutions Understand the relationship between absorbance and percent transmittance Understand the interaction of light and matter at the nano level Use a calibration curve to determine an unknown concentration	Experimentally determine the change in enthalpy given a temperature change Understand the relationship between mass and heat energy Understand the difference between exothermic and endothermic reactions Predict the sign of the change in enthalpy from a temperature change	Identify key points on a titration curve Identify the unknown analyte using the calculated pKa value Understand the reaction of a weak acid with a strong base Understand real-world applications of titrations

The faculty members were not asked explicitly about any broad learning goals; however, some learning goals were still mentioned in the course of the interview. These were noted separately and were not included in any analysis as this study was focused on experiment-specific learning objectives.

Table SI3: Skew and Kurtosis values

		Hands-On		*Virtual*	
		Skewness	Kurtosis	Skewness	Kurtosis
Beer's Law	Anxiety	0.466	-0.648	0.329	-0.602
	Emotional Satisfaction	**-1.099**	**1.074**	-0.503	-0.688
	Intellectual Accessibility	-0.759	0.158	-0.251	-0.786
	Usefulness of Lab	-0.625	0.160	-0.536	-0.598
	Equipment Usability	**-1.277**	**2.077**	-0.764	-0.235
	Open-endedness of Lab	-0.488	0.163	-0.395	-0.127
Calorimetry	Anxiety	0.724	-0.657	0.903	-0.174
	Emotional Satisfaction	**-1.580**	**1.823**	**-1.399**	**1.217**
	Intellectual Accessibility	**-1.487**	**1.501**	**-1.571**	**1.796**
	Usefulness of Lab	-0.875	1.009	-0.622	-0.126
	Equipment Usability	**-1.009**	**0.329**	**-1.487**	**2.905**
	Open-endedness of Lab	-0.296	-0.744	-0.400	-0.553
Titration	Anxiety	0.798	-0.177	0.311	-0.765
	Emotional Satisfaction	-0.976	0.640	-0.548	-0.551
	Intellectual Accessibility	-0.802	0.436	-0.624	-0.411
	Usefulness of Lab	-0.335	-0.208	-0.459	-0.615
	Equipment Usability	**-1.404**	**2.539**	**-1.010**	0.232
	Open-endedness of Lab	0.153	0.019	-0.464	-0.169

Table SI4: Affective averages by environment and experiment

		Anx	**ES**	**IA**	**U**	**EU**	**OE**
Beer's Law	Hands-On	32.71	72.28	66.10	3.78	4.21	3.54
	Virtual	35.68	60.33	57.80	3.47	3.75	3.54
Calorimetry	Hands-On	23.56	78.12	77.32	3.88	4.66	4.07
	Virtual	21.72	75.83	78.56	3.62	4.41	3.95
Titration	Hands-On	32.08	69.10	69.58	3.73	4.29	3.23
	Virtual	33.12	63.50	68.25	3.37	3.76	3.50

Scales on a 0-100 semantic differential scale: Anx: anxiety, ES: emotional satisfaction, IA: intellectual accessibility
Scales on a 0-5 point Likert-type scale: U: usefulness of lab, EU: equipment usability, OE: open-endedness of lab

Latent Profile Analysis:

Once the clustering variables were selected as: emotional satisfaction, intellectual accessibility, usefulness of lab, open-endedness of lab, and equipment usability, the R package mclust was used to conduct a latent profile analysis. The anxiety scale was not selected as a clustering variable. A latent profile analysis has an advantage over traditional distance-based cluster analysis as it allows competing models to be compared with a fit index to determine the best clustering for the data. There are fourteen different types of models compared and each of these types had nine sub-models that were used to determine the number of profiles. There were four different categories that the models could be different on: the distribution of the data within each grouping, the volume of the grouping, the shape of the grouping, and the orientation of the grouping. The first letter of the model represents whether the volume was forced to be equal between the groupings (E) or if there was variation allowed in the volume (V). The second letter of the model indicates whether the shape of the model was forced to be equal between the groupings (E) or if there was variation allowed in the shape (V). The third letter of the model specifies whether the orientation of the model was on the coordinate axes (I), forced to be equal between groups (E), or allowed to vary (V). There are two models that do not follow this lettering. EII is for spherical groups with equal volume and equal shape and VII is for spherical groupings with variable volume and equal shape. For the Beer's Law data, the r function mclustBIC was used to compare all the models on the BIC fit index:

Table SI5: BIC indices for all possible models for Beer's Law data

	EII	**VII**	**EEI**	**VEI**	**EVI**	**VVI**	**EEE**	**EVE**	**VEE**	**VVE**	**EEV**	**VEV**	**EVV**	**VVV**
1	-16501.4	-16501.4	-10475.4	-10475.4	-10475.4	-10475.4	-9655.02	-9655.02	-9655.02	-9655.02	-9655.02	-9655.02	-9655.02	-9655.02
2	-15153	-15076.6	-9880.17	-9755.95	-9877.55	-9755.02	-9620.04	-9547.8	-9458.01	-9468.32	-9571.09	-9484.68	-9572.07	-9489.55
3	-14574.2	-14422.3	-9798.39	-9594.37	-9737.39	NA	-9484.54	-9573.11	-9461.59	-9430.9	-9582.6	-9485.44	-9611.83	-9520.89
4	-14237.5	-14144.4	-9605.86	-9501.16	-9643.88	NA	-9490.44	-9540.49	**-9408.39**	-9445.8	-9586.7	-9484.16	-9625.05	-9560.75
5	-13978.2	-13905.1	-9603.75	-9497.37	-9645.41	NA	-9505.78	-9562.34	-9408.89	-9433.96	-9641.8	-9551.22	-9689.47	-9551.73
6	-13909.1	-13792.4	-9613.43	-9461.04	-9639.73	NA	-9551.32	-9587.87	-9435.61	-9467.29	-9661.99	-9576.45	-9775.14	-9626.42
7	-13765.9	-13675.8	-9568.55	-9493.52	-9686.25	NA	-9577.47	-9649.66	-9453.16	-9511.17	-9720.75	-9631.47	-9855.15	-9721.86
8	-13674.6	-13450	-9576.26	-9501.44	NA	NA	-9587.03	-9663.83	-9484.48	-9547.29	-9807.52	-9711.39	-9853.02	-9788.98
9	-13616.4	-13322.9	-9612.14	-9492.6	NA	NA	-9622.77	-9672.88	-9492.94	-9567.88	-9840.68	-9729.3	-9987.25	NA

The best fitting model is the one that produces the highest BIC, since BIC is calculated to be maximized in mclust. Therefore, the best fitting model was VEE with 4 profiles, as shown in bold in Table SI5. The grouping with five profiles had a similar fit but ultimately four was chosen as it was slightly higher and presents the simpler case. The more profiles that are selected, the harder it is to make meaningful comparisons between the profiles. This means that the groups were ellipsoidal with varying volume but equal shape and orientation. This process repeated in a similar fashion for the other two experiments. For the calorimetry experiment, the solution of five profiles had the highest BIC but after looking at the profiles, two profiles had very similar characteristics and were collapsed into one profile, resulting in four profiles used for interpretation. For the titration experiment, the solution of three profiles had the highest BIC and was selected as the best fitting.

Table SI6: Affective averages by profile and experiment

		***Anx**	**ES**	**IA**	**U**	**EU**	**OE**
Beer's Law	Low	53.73	38.26	37.76	2.59	2.45	2.67
	Medium	31.45	71.98	66.93	3.70	4.16	3.54
	High	16.57	92.85	82.99	4.35	4.84	4.35
	Mixed	53.64	7.35	19.59	3.95	4.60	3.98
Calorimetry	Low	59.28	5.95	13.18	3.82	4.41	4.09
	Medium	31.54	57.48	66.10	3.15	4.03	3.36
	High	18.03	88.08	86.61	3.67	4.54	3.82
	Very High 1	8.57	99.38	98.38	4.57	5.00	5.00
	Very High 2	12.14	96.19	92.35	4.22	4.92	4.71
Titration	Low	54.98	26.21	46.75	2.69	2.23	2.73
	Medium	34.42	64.80	66.93	3.45	4.12	3.18
	High	17.90	90.36	84.98	4.10	4.70	4.18

Scales on a 0-100 semantic differential scale: Anx: anxiety, ES: emotional satisfaction, IA: intellectual accessibility
Scales on a 0-5 point Likert-type scale: U: usefulness of lab, EU: equipment usability, OE: open-endedness of lab
*****Anxiety was not used as a clustering variable and is only presented here to inform the reader of the average scale score by profile. Similarly, the two "Very High 1" and "Very High 2" profiles were combined from the 5-profile solution to form the "Very High" profile seen in Table 5.

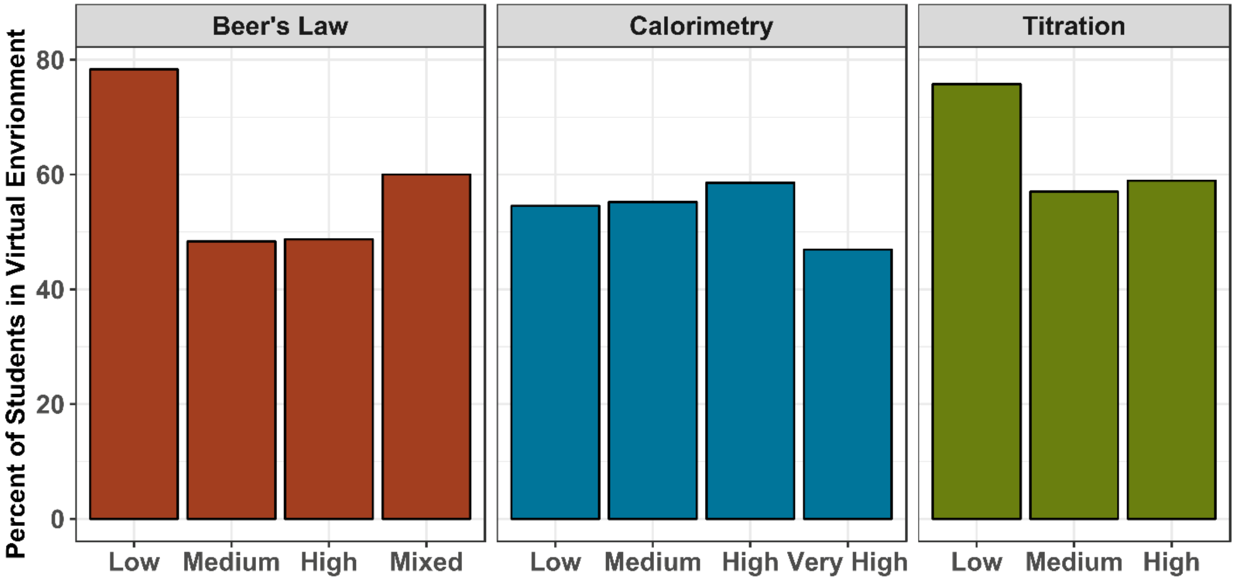

Figure SI1: Percent of students that completed the experiment in the virtual environment by profile