JOURNAL OF CHEMICAL EDUCATION
ARTICLE
pubs.acs.org/jchemeduc

Learning Dimensional Analysis through Collaboratively Working with Manipulatives

Erin K. H. Saitta,* Michael J. Gittings, and Cherie Geiger

Department of Chemistry, University of Central Florida, Orlando, Florida 32816, United States

S Supporting Information

ABSTRACT: Dimensional analysis is traditionally one of the first topics covered in a general chemistry course. Chemists use dimensional analysis as a tool to keep track of units and guide them through calculations. Although unit conversions are taught in a variety of subjects over several grade levels, many students have not mastered this topic by the time they enter college. To properly equip beginning chemistry students, a collaborative active-learning activity was developed. This article describes the activity and reports data of the effects it had on students' performance in a first-semester general chemistry course at a large research institution.

KEYWORDS: First-Year Undergraduate/General, High School/Introductory Chemistry, Chemical Education Research, Collaborative/Cooperative Learning, Hands-On Learning/Manipulatives, Mathematics/Symbolic Mathematics, Nomenclature/Units/Symbols

FEATURE: Chemical Education Research

Students often find learning dimensional analysis to be difficult. This could be caused by a variety of reasons. Researchers wonder whether students' mathematical difficulties in chemistry are due to the transfer of mathematics to the science domain. Recent studies, however, concluded that difficulties were a result of deficiencies in the students' mathematics foundation.[1] This deficiency became more pronounced when the connection between mathematics and science was required in an application field, such as chemistry.[1] Research has also noted that student perceptions of a course may influence their learning.[2] If students have negative perceptions of mathematics, it could affect their performance in a chemistry classroom. One of the issues affecting student learning is mathematics anxiety. This includes "feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of mathematical problems in a wide variety of ordinary life and academic situations".[3] The activity in this study was designed to limit complications due to mathematics anxiety by teaching patterns using pictures before introducing numbers. In addition, the mathematical concept of dimensional analysis was taught before applying it to science and chemistry.

RATIONALE AND METHODS

The pedagogy behind the teaching of the material also has a great impact on students' learning. VARK, which stands for Visual—Aural—Read/Write—Kinesthetic, can be used to construct the way that students take in and communicate information.[4] The traditional method of teaching dimensional analysis in textbooks appeals mostly to the analytical visual learner. Example problems are usually worked out displaying chemistry-based dimensional analysis mathematics problems. In addition, many college-level general chemistry classes are taught to students acting as passive listeners. The activity described in this article includes techniques that could appeal to various types of learners. The activity cards allow the students to manipulate the equations in a more hands-on way than they could with just paper and pencil. Working in groups allows students to hear themselves and peers explain their thought process as they work through the problems. Working in small groups also encourages effective and productive active learning.

Research has indicated that cooperative learning has positive effects at the college level.[5] University professors are beginning to bring active, inductive, cooperative learning into their chemistry classrooms.[6] Various educators have taken advantage of this information and have created chemistry games and manipulatives to help their students learn material for general chemistry, organic chemistry, and biochemistry.[7−9] One specific example is a card game that was previously developed to teach dimensional analysis from a physics point of view.[10] These publications are effective in providing other educators with ideas about how to best meet their students' needs. However, few published studies contain data on how these manipulatives can affect students' performance in a first-semester general chemistry course at a large research institution.

STUDY STRUCTURES AND PARTICULARS

The target population in this study consisted of 309 students enrolled in the Chemistry I course for science majors during the fall 2008 semester. In addition to the two, 90-min lectures conducted each week, students were required to enroll in a 50-min discussion session that met once a week. Discussion sessions enabled students to ask questions, practice problems, take

Published: May 13, 2011

Table 1. Timelines of Tasks for Each Group

Week 1	Week 2	Week 6
	Experimental Group	
Administer Pretest	Review Part 1 (class)	Administer Posttest
Complete Part 1 of activity (pairs)	Complete Part 2 of activity (pairs)	
	Discuss how the activity describes math (class)	
	Address common misconceptions (class)	
	Complete Part 3 of activity (pairs)	
	Hand out practice worksheet	
	Control Group	
Administer Pretest	Conventional procedure (described above)	Administer Posttest

quizzes, and review concepts in a smaller group setting. Each section was lead by one of two graduate teaching assistants (GTA). The traditional procedure of a discussion section includes the GTA solving example problems on the board and answering any questions the students may have about the lecture content, and then administering a weekly quiz. Each discussion section had less than 45 students. In this particular semester, there were eight discussion sections that met throughout one day during the week. To minimize the variable effect of the influence of the GTAs as well as the time of day, the experimental groups were chosen at various times taught by both GTAs. All participants signed a consent form to take part in the research study. A pretest was distributed to all eight sections during the first discussion session of the semester. The experimental group (N = 151) participated in the student-centered, active-learning activity during two discussion sessions, while the control group (N = 158) reviewed the material by the conventional procedure (described above). One month elapsed before a posttest was administered to all eight sections (see Table 1).

The Activity

The activity consisted of three parts, each of which met specific goals (see Table 2). The first part prompted the students to work in pairs with specially made dimensional analysis picture cards. Each card was divided in half by a horizontal line. An animal picture was depicted on the top, the bottom, or both sections of the card. If the card was turned over, the placement of the pictures was reversed. The students worked through a worksheet in pairs. The worksheet guided them through a process of arranging the pictures, drawing their arrangement on the paper, and crossing out the pictures that were the same. When properly arranged, a relationship from one animal to another was established. Two problems were started on the worksheet for the students. The third problem allowed them to set up and solve their own path.

The following week, Part 2 of the activity was completed by the students in pairs after a brief review of Part 1. This second part used the same cards as in Part 1; however, instead of the activity focusing only on the animal picture, the number of animals on the card was also taken into account. Participants began to multiply and divide to solve problems involving the arrangement of their animals. All three of the problems were guided by the worksheet. The first and second questions were based on the animal cards while the third question relied on their knowledge of the relationship between years and seconds without the added manipulatives.

A discussion was held between Parts 2 and 3 of the activity. The students were asked how this activity related to mathematics. A list of ideas was recorded and common misconceptions were addressed. Part 3 of the activity was completed with the students in pairs with a new set of cards. The new set of cards no longer consisted of pictures of animals, but of units written in words and in corresponding symbols. For example, the density card would read "mass (g)" on top of the line and "milliliters (ml)" on the bottom of the line. The inverse was on the back so the students could flip the units as they saw fit. In this worksheet, students began to use the dimensional analysis table as well as scientific units. Before the class was over, a handout of practice problems was given to each student as an additional resource.

The Instrument

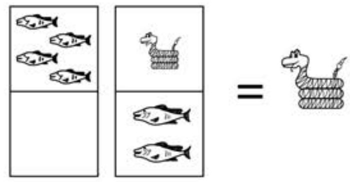
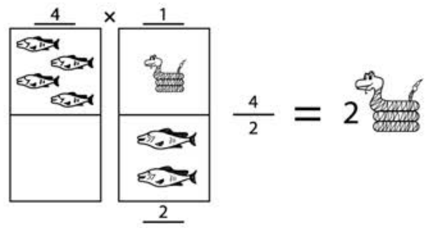
Assessment questions for the pretest and posttest were formulated to measure a variety of dimensional analysis skills. Questions ranged from basic conversion questions to multistep questions with chemistry topics. The intention of this was to better understand whether students had difficulty performing the mathematics itself or whether the difficulty occurred when the mathematics was incorporated into science content. The instruments were analyzed by three additional instructors who validated both the appropriateness of the question description and the necessary skill needed to complete the question. Both instruments consisted of free-response questions in which students were instructed to show all work. The details of each question varied between the pretest and posttest, though the type of question remained constant (see Table 3). The wording of each question and the units for each number were kept identical when possible. Example questions from the pretest and posttest are displayed below.

- Pretest Question 1: Toluene is a solvent commonly used in paint thinners. Given that the density of toluene is 0.87 g/mL, calculate the milliliters of toluene in a 5.0 g sample.
- Posttest Question 1: Limonene is used in cleansers and has a strong scent of oranges. Given that the density of limonene is 0.84 g/mL, calculate the milliliters of limonene in a 16.4 g sample.

Each question was assessed with five criteria, including whether the student:

1. Attempted the problem
2. Attempted dimensional analysis
3. Performed correct dimensional analysis
4. Performed correct mathematics
5. Produced the correct answerIf the student wrote any number or units in the answer area, they were scored as having attempted the problem. Any proof of canceling units was scored as attempting dimensional analysis. This included problems done in one step or in multiple steps but did not include cross-multiplication or division of fractions. Correct dimensional analysis was determined by the appropriate placement of numbers along

Table 2. Outline of Activity

Activity Section	Description	Objectives	Example
Part 1	Students were given a deck of picture cards that they used to complete a worksheet. They arranged them so the pictures cancel out to solve problems.	Become familiar with canceling units Understand how units can be flipped See that there is more than one way to solve a problem Finish with correct units	
Part 2	The picture cards from Part 1 were used in the same manner, except this time numbers were introduced into the questions.	Learn how to multiply and divide to solve multiple steps Progress from pictures to numerical conversions Allow some "boxes" to remain blank when needed	
Short discussion	The class created a list of the connection between the activity and mathematics. Common errors were addressed and corrected as a class.	Reflect about how the activity translates to mathematics Address common mistakes and misconceptions	Error example Incorrect placement of units 50 ml | 1000 g/ml = 0.05 g Correct placement of units 50 ml | g / 1000 ml = 0.05 g
Part 3	Students worked in pairs with a new set of cards that contained words and symbols for units. The problems were completed the same way that they were in Part 2, except now students need to find the numbers within the problem, not on the cards themselves.	Begin to work with scientific units Advance to utilizing the dimensional analysis table Successfully use new units Progress from everyday examples to scientific examples Complete word problems	grams (g) / milliliters (ml) × milliliters (ml) = grams (g) Is the same as grams / milliliters | milliliters = grams
Practice problem handout	A practice problem worksheet containing an attached answer key with worked out answers was given to the students for an additional resource.	Increases confidence Decreases amount of time needed to complete problem solving	Example practice problem: How many milligrams of $MgCl_2$ are in 0.0065 kilomoles of $MgCl_2$? The molar mass of $MgCl_2$ is 95.21 g/mol.

with either a dimensional analysis table or multiplication or division symbols. If a student showed any type of mathematically sound method of solving the problem, he or she was scored as having performed correct mathematics. If a student reported the correct answer, regardless of significant figures, that answer was scored as correct. The internal reliability coefficients for the pretest and posttest were 0.84 and 0.81, respectively.

Statistical Analyses

Statistical analyses were performed on collapsed data after an integer was assigned for each of the criteria evaluated. If the criterion was met, it was assigned 1 point. If it was not met, it was assigned a score of 0. Using the same five criteria described above, 7 assessment questions were evaluated with a total of 35 points possible. The pretest and posttest results were analyzed using a two-sample *t*-test for the difference between two means of a large sample.[11] In this context, it is testing whether a difference existed between the experimental group and the control group when their pretests were compared as well as when their posttests were compared at a 95% confidence interval. Any *t*-test score lower than 0.05 indicates a significant difference and can be seen in Table 4 in the "Significance, Pretest" and "Significance, Posttest" columns.

The null hypothesis for the pretests states that no difference exists between the two groups. The results, shown in Table 4, display that the null hypothesis fails to be rejected in all but four

Table 3. Descriptions of Assessment Questions

Question	Description	Dimensional Analysis Skill Needed
1	A science fact incorporated into a density problem	Work with chemistry vocabulary and divide by density
2	Three-step problem with a chemistry topic	Convert to a smaller base unit, multiply by molar mass, and convert to a smaller unit
3	Basic conversion	Convert from milli- unit to base unit
4	One-step problem with an "everyday" topic and units	Divide two numbers
5	Two-step problem with an "everyday" topic and "uncommon" units. One extraneous number.	Choose which number and units are most appropriate; Multiply two numbers
6	Long word problem with a chemistry topic and excess information	Work with chemistry vocabulary; Multiply two numbers
7	One-step problem with a chemistry topic	Divide by molar mass

Table 4. Values To Determine Significance between Groups for Pretest and Posttest

Question	Criteria for Evaluating Responses	Mean Difference, Control	Mean Difference, Exp.	Significance, Pretest	Significance, Posttest	No Significant Change	Significant Change
1	Try answer	0.04	0.11	0.030	0.978	X	
	Attempt D. Analysis	0.11	0.37	0.114	0.001		X
	Correct D. Analysis	0.12	0.38	0.092	0.000		X
	Correct Math	0.22	0.33	0.065	0.878	X	
	Correct Answer	0.21	0.28	0.108	0.649	X	
2	Try answer	0.23	0.31	0.172	0.690	X	
	Attempt D. Analysis	0.50	0.63	0.181	0.108	X	
	Correct D. Analysis	0.34	0.35	0.188	0.488	X	
	Correct Math	0.20	0.25	0.164	0.713	X	
	Correct Answer	0.25	0.31	0.092	0.805	X	
3	Try answer	0.00	0.04	0.135	0.328	X	
	Attempt D. Analysis	0.41	0.52	0.918	0.014		X
	Correct D. Analysis	0.40	0.47	0.838	0.239	X	
	Correct Math	0.29	0.32	0.374	0.185	X	
	Correct Answer	0.17	0.23	0.214	0.860	X	
4	Try answer	0.01	0.00	0.537	0.309	X	
	Attempt D. Analysis	0.18	0.35	0.482	0.013		X
	Correct D. Analysis	0.22	0.35	0.947	0.017		X
	Correct Math	0.10	0.17	0.615	0.016		X
	Correct Answer	−0.02	0.05	0.746	0.034		X
5	Try answer	0.18	0.29	0.167	0.145	X	
	Attempt D. Analysis	0.25	0.39	0.667	0.025		X
	Correct D. Analysis	0.28	0.39	0.372	0.173	X	
	Correct Math	0.30	0.47	0.003	0.704	X	
	Correct Answer	0.30	0.45	0.012	0.548	X	
6	Try answer	0.26	0.30	0.109	0.259	X	
	Attempt D. Analysis	0.37	0.44	0.868	0.237	X	
	Correct D. Analysis	0.27	0.32	0.748	0.275	X	
	Correct Math	0.32	0.33	0.249	0.639	X	
	Correct Answer	0.20	0.30	0.109	0.851	X	
7	Try answer	0.13	0.19	0.176	0.958	X	
	Attempt D. Analysis	0.43	0.64	0.063	0.013		X
	Correct D. Analysis	0.39	0.64	0.013	0.003		X
	Correct Math	0.20	0.40	0.135	0.004		X
	Correct Answer	0.22	0.39	0.107	0.055		X

of the 35 points. This means that no statistical difference was found between the two groups at the beginning of the study in those criteria. In all of the areas where they differed, the experimental group scored significantly lower than the control group. Therefore, before the activity took place, the two groups of students scored relatively the same with the exceptions occurring when the experimental group scored lower. The null hypothesis for the posttest states that no agreement exists between the experimental and control groups. The results in Table 4 show that the null hypothesis was rejected for 12 out of

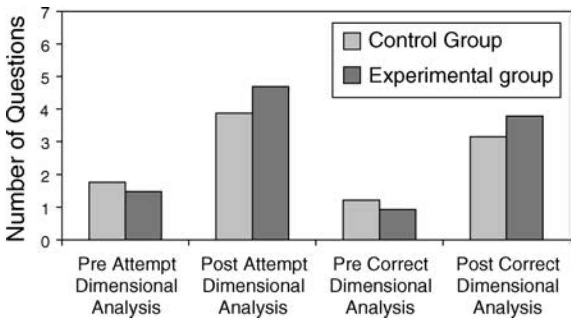


Figure 1. Summed averages for dimensional analysis criteria. If the criteria were met for each question, a value of 7 would be achieved. In both cases, the experimental group went from scoring statistically the same as the control group to scoring statistically higher.

the 35 cases. In each of the 12 cases, the experimental group outperformed the control group.

■ RESULTS

The data were categorized as either having no change or having a significant change. To be considered a significant change, the criterion had to either be not significant in the pretest and significant in the posttest; or, be significant in the pretest and not significant in the posttest. The data reported for the four points that initially rejected the null hypothesis were subjected to ANCOVA to account for the pretest differences. A significant change was found for 12 of the cases, all of which were in favor of the experimental group. The activity did not produce any significant changes in performance on Questions 2 and 6. The difference in means between the pretest and posttest are reported in Table 4.

Averages of the sums were calculated to gain a better understanding of the overall impact of the activity. Figure 1 shows the significant changes in students attempting dimensional analysis (t-test results: pre = 0.254, post = 0.001), as well those scores where dimensional analysis was performed correctly (t-test results: pre = 0.162, post = 0.016). In both cases, the experimental group went from scoring statistically the same as the control group to scoring statistically higher. The experimental group scored statistically lower than the control group on the pretest regarding trying to answer the question and producing the correct answer. No statistical difference was found in the use of correct mathematics between the experimental and the control group. The variance accounting for the two different teaching assistants was zero and therefore had no impact on the activity.

Student Response

Students who participated in the activity were asked to leave comments at the end of the posttest assessment. Out of the 151 students, 108 did not comment on the activity; 43 students left a variety of comments ranging from what they did or did not like to what improvements could be made for future classes. Each comment was grouped and classified as positive, negative, or irrelevant. Many students left more than one comment. As shown in Figure 2, 71 of the responses were positive, 21 were negative, and 3 were considered irrelevant to the activity. An example of an irrelevant comment was "I'm hungry". The most common response was a positive response indicating that the student thought the activity was helpful. The most common negative comment was the student thought they already knew the material. Additional comments and their frequency can be seen in Table 5.

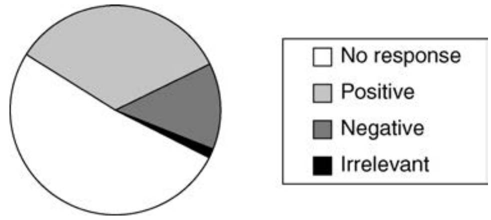


Figure 2. Distribution of total student responses.

Table 5. Overview of Students' Comments

Negative Comments (21 Total)	Comments, N	Positive Comments (71 Total)	Comments, N
Already knew the material	8	Helpful	28
Too simple; Wanted harder problems	4	Sufficiently taught the material	12
Took too much class time	4	Enjoyed activity	11
Too childish; Did not like animal cards	3	Liked animal cards	9
Need more explanation	2	Helped them outside of the classroom	3
Confusing	2	Easy to understand	3
Need more time to complete	2	Thank you	3
Too repetitive	2	Like working in groups	2
Do not like group work	1		

Discussion

In this research project, both the method of achieving an answer and the answer itself were of importance. Students who participated in the research activity were more successful than the control group at solving problems through dimensional analysis. Further insight can be gained about the impact of the activity when the individual topics assessed are analyzed. Questions 1, 4, and 7 were the most affected by the activity. These questions include both everyday problems and simple science-related problems. Confidence in dimensional analysis as a problem-solving tool improved, as seen by the increase in attempted use of dimensional analysis by the experimental group for five of the seven questions. This confidence could be beneficial when stoichiometry is introduced because dimensional analysis is the preferred method of problem solving.[12,13] The experimental group was also more successful than the control group at setting up the dimensional analysis table in a mathematically correct manner, as seen in three of the seven questions.

The students were instructed to show all of their work but were not instructed how to solve the problem. Therefore, various types of mathematical methods were used. The posttest demonstrates that fewer students in the experimental group relied on alternate mathematics techniques such as cross-multiplication, which was the most common method students used when dimensional analysis was not attempted.

Student performance on Questions 2 and 6 was not affected by the activity. Both of these questions were more complex in terms of the number of steps needed to solve the problem as well as the amount of information in the question. It is unknown whether any differences in students' abilities existed at the end of the course.

■ CONCLUSION AND IMPLICATIONS FOR CHEMISTRY TEACHERS

The student-centered aspect of the activity let the participants take control of their own learning. Working in pairs allowed the students to proceed at their own pace and in their own way. The cards allowed students to think through and set up the problems before writing on their worksheet. To limit the amount of mathematics anxiety that could impede learning, animal pictures were used to teach the pattern before numbers and science words were introduced. At first glance, the activity may appear too juvenile for the adult students; nevertheless, in the hope of simplifying the method and lowering mathematics anxiety, animals were chosen for the initial part of the study because of their relatively universal appeal. In addition, a class discussion was held in order to reiterate the connection to mathematics and to avoid common errors. Data revealed that students who participated in the activity had significant changes in their performance pertaining to: (i) attempting dimensional analysis; (ii) setting up the dimensional analysis correctly; and (iii) producing the correct answer when compared to the control group. This implies that the activity is effective for college-level general chemistry students.

Unit conversions are often introduced in middle school and high school, so this activity may help secondary students. In addition to a classroom activity, it is probable that this would transfer well into a tutoring activity. Depending on the level of students, it is expected to be effective as both an advanced activity and remedial activity to supplement current methods used in the classroom. New cards could be made each time a new unit is introduced and could be used throughout an entire semester. Some students who participated in this activity reported using the cards to help guide them through their homework problems. Further studies are required to reveal the activity's impact on additional populations.

■ ASSOCIATED CONTENT

Supporting Information

Animal cards; unit cards; student worksheet; teacher answer sheet. This material is available via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: erin.saitta@ucf.edu.

■ ACKNOWLEDGMENT

We would like to acknowledge the chemistry I students who participated in this research study, as well as Debbie Maxwell and Simone Novas-Card who served as the TAs for the course. We would also like to acknowledge Charles Dziuban and Patsy Moskal for the statistical analysis of the data and John Martin for digital formatting. Finally, we acknowledge Tamra Legron, Rebecca Albo, and Todd Gatlin for technical assistance.

■ REFERENCES

(1) Potgieter, M.; Harding, A.; Engelbrecht, J. *J. Res. Sci. Teach.* **2008**, *45*, 197–218.
(2) Carter, C. S.; Brickhouse, N. W. *J. Chem. Educ.* **1989**, *66*, 223–225.
(3) Richardson, F. C; Suinn, R. M. *J. Counseling Psychol.* **1978**, *19* 551–554.
(4) Fleming, N. D.; Mills, C. *To Improve the Academy* **1992**, *11*, 137.
(5) Doymus, K. *J. Chem. Educ.* **2007**, *84*, 1857–1860.
(6) Felder, R. M. *J. Chem. Educ.* **1996**, *73*, 832–836.
(7) Myers, S. *J. Chem. Educ.* **2003**, *80*, 423–424.
(8) Welsh, M. J. *J. Chem. Educ.* **2003**, *80*, 426–427.
(9) Joao Costa, M. *J. Chem. Educ.* **2007**, *84*, 977–978.
(10) Machacek, A. C. *Phys. Educ.* **2001**, *36*, 141–144.
(11) Larson, R.; Farber, B. *Elementary Statistics Picturing the World*, 2nd ed.; Prentice-Hall, Inc.: Upper Saddle River, NJ, 2003; pp 390−393.
(12) Brown, T.; LeMay, H. E., Jr.; Bursten, B. E. *Chemistry: The Central Science*, 8th ed.; Prentice-Hall, Inc.: Upper Saddle River, NJ, 2000; pp 24−26.
(13) Kotz, J. C.; Treichel, P. M.; Weaver, G. C. *Chemistry and Chemical Reactivity*, 6th ed.; Thomson Brooks/Cole: Belmont, CA, 2006; p 42.