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Improving student learning of organic chemistry by the use of case comparisons.

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Improving Student Learning of Organic Chemistry

By The Use of Case Comparisons

By

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And

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INTRODUCTION

Organic Chemistry remains a course taken by a huge number of undergraduates as a course requirement or as a prerequisite for entry into a host of post-undergraduate fields of study such as, medicine, pharmacy, and dentistry (Association of American Medical Colleges, 2013; American Dental Association, 2013; American Association of Colleges of Pharmacy, 2013). As a sub-discipline of chemistry involving the scientific study of the structure, properties, and reactivity of organic compounds (i.e., compounds predominantly containing carbon atoms), organic chemistry is regarded as a fundamental science owing to its wide reaching importance in many fields including, but not limited to, drug development, natural product synthesis, and food production. While published data is lacking on the current pass rates in organic chemistry courses nationwide, general consensus indicates that organic chemistry presents significant problems for many college undergraduates, with lots of academic institutions indicating low pass rates in the course (Szu et al. 2011). A host of measures have been taken by these institutions to increase pass rates. These measures have varied from incorporating cooperative learning into the classroom (Hagen, 2000; Paulson, 1999) to doing web-based assignments prior to class (Collard et al. 2002). A few of these methods have been shown to successfully increase pass rates in organic chemistry and another method that holds promise is the utilization of case comparisons.
Previous research has shown that the use of analogies as instructional tools positively facilitates the process of student learning (Alfieri, Nokes-Malach, and Schunn, 2013; Schustack & Anderson, 1978; Weller, 1970). The use of analogies as instructional tools pertain to the premise that novel information could be conveyed to a set of learners by showing some relation to instances or examples they are currently conversant with (Loewenstein & Thompson, 2000). As an example, a common reaction typically encountered in organic chemistry is the SN2 reaction which is essentially a bimolecular nucleophilic substitution where an electron rich specie donates electrons to an electron poor specie. Comparing this reaction to people dancing at a party with two different characters coming and going in opposite directions as a means of explaining the different characteristics of the reaction provides a reasonable mental framework for acquiring the new knowledge that is spelled out. “Analogical learning” as it is so called typically focuses on providing examples that learners could extract key concepts and principles from which can in turn be extrapolated to newer situations that in a way reflect some commonalities with respect to the examples shown initially (Gentner, Loewenstein, and Thompson, 2003; Gick & Holyoak, 1980). The prior exposure to examples takes advantage of the individual’s ability to compare familiar or unfamiliar things. A common technique employed in “analogical pedagogy” involves the use of case comparisons.

Case comparisons revolve around methods of concept acquisition that emphasize the identification of relationships from a set of carefully selected instances that attempt to highlight the concept being taught (a method of inductive learning). Many of these studies have shown that case comparisons conducted with appropriately weighted parameters facilitate the process of extracting useful principles or core concepts from the exemplars presented (Gentner et al, 2003; Tennyson, 1973). When presented with varying examples all highlighting the same underlying
principles, case comparisons provide opportunities to see relationships across the cases presented, notice common features/underlying themes, make useful inferences, and then build relevant mental models pertaining to the subject matter. These “derived models” are then typically applied to newer instances that lend themselves to the application of the principles highlighted in the “observation phase,” the period during which the mental models were built (Gentner, 2010). For example, presenting comparisons between the Solar system (with the sun and the 8 planets revolving around it) and the different components of an atom that move in orbits around the nucleus could emphasize the principle of smaller units revolving around a larger unit as a result of attractive forces operating between them (Loewenstein, Thompson, Gentner, 2010). This case comparison could be used to explain concepts from Newton’s Laws and rotational kinematics in the realm of physics.

The acquisition of these learned relationships provide participants with new memory cues that could be applied to new instances. Exposure of the experimental participants to newer instances after the acquisition of cues through case comparisons has typically been followed with successful results. For instance, in an experiment conducted by Rittle-Johnson and Star (2007), a group of 7th graders were given opportunities to compare two different approaches to solving the same algebraic problem. This problem involved solving multistep linear equations with the aim of extracting the relevant principle of using composite variables. Students involved in the experiment were not given any prior instruction on the principle save for a set of statements highlighting what steps were taken to arrive at the solution. Participants in the experimental group were able to make many conceptual and procedural inferences from the comparison presented to them, and they learned more than participants who saw the same material without comparing. The “case comparison” group performed much better than the group that even saw
the exact same material prepared in sequential fashion. An example of the aforementioned experiment is shown in Figure A;

**A. Compare Condition**

<table>
<thead>
<tr>
<th>Mandy’s Solution:</th>
<th>Erica’s Solution:</th>
</tr>
</thead>
<tbody>
<tr>
<td>5(y + 1) = 3(y + 1) + 8</td>
<td>5(y + 1) = 3(y + 1) + 8</td>
</tr>
<tr>
<td>5y + 5 = 3y + 3 + 8</td>
<td>Distribute</td>
</tr>
<tr>
<td>5y + 5 = 3y + 11</td>
<td>Combine</td>
</tr>
<tr>
<td>2y + 5 = 11</td>
<td>Subtract on Both</td>
</tr>
<tr>
<td>2y = 6</td>
<td>Subtract on Both</td>
</tr>
<tr>
<td>y = 3</td>
<td>Divide on Both</td>
</tr>
</tbody>
</table>

1. Mandy and Erica solved the problem differently, but they got the same answer. Why?

2. Why might you choose to use Erica’s way?

**B. Sequential Condition**

<table>
<thead>
<tr>
<th>Mandy’s Solution:</th>
<th>Erica’s Solution:</th>
</tr>
</thead>
<tbody>
<tr>
<td>5(y + 1) = 3(y + 1) + 8</td>
<td>10(x + 3) = 6(x + 3) + 16</td>
</tr>
<tr>
<td>5y + 5 = 3y + 3 + 8</td>
<td>Distribute</td>
</tr>
<tr>
<td>5y + 5 = 3y + 11</td>
<td>Combine</td>
</tr>
<tr>
<td>2y + 5 = 11</td>
<td>Subtract on Both</td>
</tr>
<tr>
<td>2y = 6</td>
<td>Subtract on Both</td>
</tr>
<tr>
<td>y = 3</td>
<td>Divide on Both</td>
</tr>
</tbody>
</table>

1. Would you choose to use Mandy’s way to solve problems like this? Why or why not?

----NEXT PAGE----

1. Check Erica’s solution by substituting her answer into the equation. Did Erica get the right answer?

Figure A - Case comparison example from Rittle-Johnson and Star (2007).
Comparisons have been shown to be helpful across many ages (3 year olds to adults) and across multiple domains (business negotiations, algebra, categorization of objects during word learning, educational psychology etc.) in effect showcasing the innate ability of humans to categorize things based on inherent similarities and differences (Loewenstein et al, 2003; Nagarajan & Hmelo-Silver, 2006; Namy, Gentner, & Clepper, 2007).

A host of these comparison studies have been done in many fields spanning the natural and social sciences, but none to my knowledge has been done in the field of organic chemistry.

Why may case comparisons be useful for organic chemistry? Unlike some subjects that rely on extensive memorization, organic chemistry is one that presents many interesting opportunities for pattern recognition. Nelson (2000) expanded on the benefits of making organic chemistry at the undergraduate level much easier to learn by creating study aids that organize the information for students. She accomplished this by following in the steps of the great chemist, Dmitry Mendeleev, who performed a similar feat with the periodic table. Just as Mendeleev arranged elements with similar characteristics in the same columns in the periodic table, Nelson, arranged Nucleophiles and Electrophiles pertaining to a host of organic chemistry reactions by similarities they possessed (she did this on two separate sheets of paper). This ubiquitous arrangement made it possible for students to juxtapose these two sheets as an aid in visualizing the mechanisms of the respective reactions (Nelson, 2000). An outgrowth of this was the added possibility of students being able to use the guide to identify potential reactions that had not been given to them. The study aids utilized by Nelson essentially served to clearly delineate patterns in the reactions of a host of organic compounds with the students in the experimental “study aid”
group (who used the resource outside of class) showing a 20% higher test score than the control group that did not use the resource outside of class.

Further credence could be lent to the usefulness of case comparisons as tools for teaching organic chemistry when chemical reactions are considered. Many reactions in organic chemistry (at least at the undergraduate level) follow the same pattern of a nucleophile, (defined as an electron rich species) reacting with an electrophile, (defined as an electron poor species) to result in the formation of a product. A host of interesting patterns could be identified in these reactions along with many other areas of organic chemistry, which could hypothetically contribute to applying similar patterns to newly encountered situations that emphasize the same general theme.

In contrast with Nelson’s experiment which implicitly nudges individuals towards making comparisons, our goal with the current experiment involved explicitly making the participants make the comparisons themselves. The research literature shows the process of getting people to explicitly make comparisons themselves in the presence of concept examples to be more effective than just showing them examples of the concept (Catrambone & Holyoak, 1989). In addition, our experiment attempts to manipulate just comparison (the independent variable), with all other factors of the experiment being held constant as opposed to Nelson’s study which was not as tightly controlled (with regards to control factors that were utilized in the current experiment like the maintenance of similarities in pretests and posttests taken with the only variable across board being the training conditions). Tight control ensures that the effects being tested for are isolated purely to minimize interactions with other factors that could skew experimental results.
Current Study

The main goal of the current experiment was to utilize case comparisons to test for improvements in the learning of a concept taught in many organic chemistry curriculums nationwide (resonance).

The concept of resonance is one typically taught in the first semester of a regular organic chemistry college curriculum. Resonance essentially aims to show how compounds maintain stabilities by reducing the absolute concentration of electrons on any one spot in the molecule (akin to diversifying one’s investments to avoid unnecessary risks). Drawing applicable resonance structures for a molecule typically involves moving electrons (present as lone pairs, single radical electrons, or pi bonds) across the different elements of a compound while keeping cognizance of rules that pertain to the accurate representation of Lewis structures (like the octet rule). Resonance presents an ideal domain for making comparisons as a large percentage of attendant structures reflect a couple of trends that if properly identified, could be applied to most other examples encountered.

To test the effectiveness of case comparisons, the experiment would be conducted under 3 different conditions. In the first condition (the Good Comparison condition), participants were exposed to a series of well-matched examples showing pairs of resonant and non-resonant structures. The examples were matched by similarities in characteristics like the size of the compounds used and the elements that were used in the structures. In the second condition (the Random Comparison condition), participants were also exposed to pairs of resonant and non-resonant structures, but these pairings were randomly chosen. In the third condition (the Sequential condition), participants were exposed to one resonant or non-resonant structure at a time (not pairs). All participants took a pre-test (to establish a baseline, identical for all
participants) prior to the training phase of the experiment. Then all participants completed a training phase where they studied structures, and the presentation of these structures differed by condition. At the end of the experiment, participants took a post-test (same test for all conditions) with the scores being used to measure changes in knowledge that had been made over the course of the experiment and overall knowledge at the end of the experiment.

Hypotheses

The careful selection of chemical structures meeting certain pre-defined criteria in terms of similarities (and differences) built into a well-ordered case comparison experiment should improve student acquisition of knowledge in organic chemistry more than seeing the same structures randomly paired or seeing the same structures sequentially (in other words, without comparison).

METHODS

Participants

A group of 46 students consisting mostly of psychology majors and other randomly selected individuals from The University of Louisville were selected to participate in the study. About 60% of the participants signed up for the experiment using the SONA credit sign up system utilized by the Department of Psychology and Brain Sciences. All the students that were signed up through the SONA system were members of the PSYC 201-Introduction to Psychology class. The other 40% of participants were randomly chosen psychology majors, and majors in other disciplines like biology, mostly from other psychology labs at the university. Of the 46 participants in the experiment, 24 had varying degrees of college chemistry experience (not surprising considering the General Education requirements at the university), 18 had high
school/Advanced Placement chemistry experience, and 4 either had no experience or did not respond to the questionnaire.

**Design**

The experiment used a pre-test-training-post-test design. The experiment contained 3 different conditions based on the presentation of training images participants were exposed to;

a) The *Good-Comparison* condition was exposed to 10 training slides containing two structures each with one structure being resonant and the other being non-resonant. The structures were carefully chosen using various parameters like similarities in elements, size of compound, and heteroatoms present (defined as non-carbon atoms, etc.). These structures were chosen with these parameters in mind to provide excellent comparison opportunities where a reasonable observation of certain important patterns could be observed.

b) The *Random-Comparison* condition was exposed to 10 training slides containing two structures each with one structure being resonant and the other being non-resonant. The structures were randomly paired with no recourse made with respect to closely matching parameters such as those used in the *Good-Comparison* condition. We created two versions of randomly paired structures to ensure that any differences between conditions were not due to a particular random ordering of structures.

c) The *Sequential* condition utilized the exact same order of structures used in the *Random-Comparison* condition with the only difference being that the structures were arranged sequentially (one at a time) in 20 training slides in contrast to the 10 pairs of 2 structures each used for the *Random-Comparison* condition. Again, we created two versions of randomly
ordered structures to ensure that any differences between conditions were not due to a particular random ordering of structures.

It should be noted that 60 structures, with 30 being resonant and 30 being non-resonant, were created for purposes of conducting the experiment. 20 were used for the pre-test, 20 were used for the training phase, and 20 were used for the post-test. A complete list of structures can be found in Appendix A.

**Procedure**

The experiment began with all participants across all conditions taking the pre-test. The pre-test was made of 20 structures presented on PowerPoint slides, which the participants had to label on a worksheet as being resonant or non-resonant. With this stage completed, participants for the respective conditions were led into their training phases and then exposed to PowerPoint slides containing paired resonant/non-resonant structures for the comparison condition or sequential resonant or non-resonant structures for the sequential condition. Participants for each of the comparison conditions were instructed to look at each training slide for a minimum of 40 seconds, while the participants in the sequential condition were told to spend a minimum of 20 seconds studying each slide.

At the end of the training stage of the experiment, participants across all conditions were then given a post-test consisting of 20 structures presented on PowerPoint slides, with a worksheet for labeling each structure as resonant or non-resonant. It should be noted that the structures used in the post-test were isomorphic (very close in characteristic) to those that were used in the pre-test.
Upon completion of the post-test, participants were asked to fill out a short questionnaire detailing a few key pieces of information, such as elucidating on the observations that guided their choices of structures being classified as resonant or non-resonant. In addition, questions were posed about their respective majors and past chemistry histories.

Data Analysis

To test for an overall difference between conditions, we ran an analysis of covariance (ANCOVA) model, using condition as a between-subjects factor, participants’ pretest scores as a covariate, and participants’ posttest scores as the dependent variable. This allowed us to test whether the training affected participants’ posttest knowledge after accounting for differences in pretest knowledge. We also ran three planned contrasts to test for differences between individual conditions (Good-Comparison vs. Random-Comparison, Good-Comparison vs. Sequential, and Random-Comparison vs. Sequential). For these three planned contrasts, we reduced the chance of obtaining false-positive results by using a Bonferroni correction, and only tests with a p-value less than 0.017 were considered significant. Also, we ran an ANOVA model and set of planned contrasts using condition as a between-subjects factor and participants’ gain scores from pretest to posttest as the dependent variable. This allowed us to test the improvements over the pretest for the three different conditions. We also asked participants in a post-test survey to indicate the factors they concentrated on during the training phase of the experiment in a determination of a structure as being resonant or non-resonant. We report descriptive results on these data.

RESULTS

Differences between Versions of Randomly Ordered Structures

We ran ANCOVA models to ensure that our two versions of the Random-Comparison condition and two versions of the Sequential condition did not result in different posttest
performance. For the Random-Comparison condition, there were no significant differences between posttest average scores for the two different versions (1 and 2), $F(1, 12) = 1.936, p = .189, \eta^2_p = .139$. For the Sequential condition, there were no significant differences between posttest average scores for the two different versions (1 and 2), $F(1, 12) = .370, p = .554, \eta^2_p = .030$. Due to the fact that there were no differences between these versions for either condition, we collapsed across versions for all future analyses.

**Pretest**

There were no significant differences overall between our conditions on the pretest, $F(2, 43) = 3.032, p = .059, \eta^2_p = .124$. We also found no significant differences in our planned contrasts to test differences between individual conditions ($p$’s > .033). Recall that due to our multiple contrasts, our Bonferroni adjustment means that only $p$-values below .017 are considered significant.

In fact, very few people had any knowledge of resonant structures before the training. The overall mean from all 3 conditions tested was 51.85% correct (see Figure 1a), which is consistent with making random guesses on the pretest (as there were only 2 choices for right answers-resonant or non-resonant, chance performance was 50% correct).
Figure 1. Means by experimental condition for: a) pre-test scores, b) post-test scores, and c) gain scores. Note that the post-test means reported are estimated marginal means to account for differences at pretest.
Effects of Condition on Outcomes

Overall, people were getting an average of 71.41% correct on the post-test (see Figure 1b). There were no significant differences between our conditions on the posttest, even after accounting for pretest scores, although a moderate effect of condition was observed, $F(2, 42) = 1.755, p = .185, \eta^2_p = .077$. For our planned contrasts of the Good Comparison and Random Comparison groups, there was not a significant difference between conditions, although a moderate effect of condition was observed, $F(1, 42) = 2.236, p = .142, \eta^2_p = .051$. For our planned contrasts of the Good Comparison and Sequential groups, there was not a significant difference between conditions, although a moderate effect of condition was observed $F(1, 42) = 2.835, p = .100, \eta^2_p = .063$. For our planned contrasts of the Random Comparison and Sequential groups, there was not a significant difference between conditions, $F(1, 42) = 0.012, p = .914, \eta^2_p < 0.001$. While none of our conditions performed significantly differently from the others, the Good-Comparison condition had the highest posttest score.

We also looked at the gain scores as a means of measuring improvements in the post-tests when compared with the pre-tests across the different experimental conditions. Overall, people were getting about 71.4% correct on the post-test (see Figure 1c). There were no significant differences between our conditions on their gains, although a moderate effect of condition was observed, $F(2, 43) = 1.357, p = .268, \eta^2_p = .059$. For our planned contrasts of the Good Comparison and Random Comparison groups, there was not a significant difference between conditions, $F(1, 43) = 0.029, p = .865, \eta^2_p = .001$. For our planned contrasts of the Good
Comparison and Sequential groups, there was not a significant difference between conditions, although a moderate effect of condition was observed, \( F(1, 43) = 2.300, p = .137, \eta_p^2 = .051 \). For our planned contrasts of the Random Comparison and Sequential groups, there was not a significant difference between conditions, although a moderate effect of condition was observed, \( F(1, 43) = 1.755, p = .192, \eta_p^2 = .039 \).

Features Attended to During Training

Overall, people paid attention to the presence of double bonds, plus and minus signs, molecular symmetry, and similarities in the kinds of elements in determining if a structure were resonant or non-resonant. This assertion is based on the responses highlighted by the participants in the survey that accompanied the posttest at the end of the experiment. 24 individuals (about 50% of participants, let’s call them the DOUBLE BOND GROUP) based their decisions on structures being resonant/non-resonant based on the presence of double bonds (which many of them identified as equal signs), plus and minus signs, and lone pairs of electrons (which many of them counted as dots). 12 individuals (about 25% of participants, let’s call them the OCTET GROUP) mentioned a consideration of the ability to re-arrange electrons without disobeying the octet rule (which is known to a good number of people with any kind of chemistry background). A tiny number (4 individuals; about 8% of participants, let’s call them the SIZE GROUP) made decisions based on factors like size and complexity, molecular symmetry, and balance. Other participants (6, let’s call them the NO RESPONSE group) simply guessed or did not respond to the survey question. In the context of resonance as taught in many organic chemistry classes, the double bond group and the octet group (totaling 75% of participants) focused on factors that
would be regarded in most chemistry circles as being important to the determination of a structure as being resonant or non-resonant.

![Graph showing factors attended to during training as a function of the number of experimental participants.](image)

**Figure 2**-Factors Attended to During Training as a Function of the Number of Experimental Participants

**Discussion**

As the results of the study shows, there were no significant differences between the pretest scores for the different conditions. There were also no significant differences between the posttest scores across the different conditions although the Good-Comparison condition performed better than the Random-Comparison condition, which in turn performed better than the Random-Sequential condition and there were moderate effects. There were also no significant differences between gain scores for all conditions studied although the Good-
comparison condition gained more than the Random-Comparison condition, which in turn gained more than the Random-Sequential condition and there were moderate effects.

A look at the raw means, estimated marginal means and gain scores from the experiment shows that the Good Comparison condition has the highest posttest scores and gains, the Random Comparison condition has similar posttest scores to the Sequential condition but similar gain scores to the Good Comparison condition. This is trailed by the Sequential condition which recorded the lowest posttest scores and gain scores. This disparity could be explained by the initial differences in pretest scores across the different conditions. With a lower average pretest score and a similar posttest score to the Sequential condition, the Random-Comparison condition shows an apparently higher gain than would be observed if pretest averages were roughly similar across the different conditions. Sample size effects may have played a possible role in deriving these results as a normalization of the respective averages by taking pre-test scores into consideration (as a covariate for the ANCOVA analysis of the posttests) reveals close similarities between the Random Comparison condition in comparison with the Sequential condition. The utilization of an ANCOVA model for the posttest score analysis (Estimated Marginal Means), tries to correct for the lower pre-test average observed in the Random-Comparison condition and the higher pre-test average in the other conditions. A larger sample size would probably have reflected the trend and also produced more significant data as a few outliers for each condition could possibly have skewed the results in certain unusual directions. A larger sample size would be more attuned to smoothing out the statistical metrics. In addition, with a larger sample size, participants would ideally have roughly equal pretest averages between conditions. Moderate effects were often observed with the posttest scores and gain scores across the different
conditions which indicates that significant differences would probably be found with a larger sample size.

Overall, there were no significant differences between the different conditions. However, a case is to be made for the trends and effect sizes observed across multiple metrics in the experiment. It is really important to note that the participants between the different conditions were able to record differences and gains in knowledge after seeing identical structures albeit with different presentations over a short period of less than seven minutes. These results show the power in presenting the same information from a comparison perspective as opposed to presenting the same information sequentially given similar lengths of time. Overall, the Good Comparison experimental condition performed better than the Random Comparison condition which in turn performed better than the Random Sequential condition. This trend is congruent with our original hypothesis and the current research literature dealing with case comparisons which has been performed in other fields (Catrambone & Holyoak, 1989; Loewenstein, Thompson, & Gentner 2003; Nagarajan & Hmelo-Silver, 2006; Namy, Gentner, & Clepper, 2007). These results suggest that well-structured comparisons aid the process of acquiring knowledge by providing avenues to retrieve relevant principles by comparing and contrasting carefully chosen instances that attempt to highlight the principle(s) in question. By making comparisons between these exemplars, opportunities are given to make discoveries relevant to the area being studied. This has been shown to be a successful strategy in many fields of learning (Rittle-Johnson & Star, 2007; Gentner et al, 2003; Tennyson, 1973).

Case comparisons have been shown in many fields of the sciences (social and natural) to provide improvements in knowledge. The results of this experiment show the promise of case comparisons in areas of study like organic chemistry. Given the inherent nature of organic
chemistry as a science that in many cases follows well observed trends for most of its conceptual information, the application of the principles underlying case comparisons bodes well for future improvements in the way the subject is taught (considering its vital importance for many fields of study and its numerous applications to human life).

**Future Directions**

Possible considerations for studies of this nature in the future could include conducting the same experiment with a much larger sample size. In addition, case comparison studies could be done using other variables from organic chemistry (instead of resonant/non-resonant structures). Furthermore, future study participants could be made to go through these experiments prior to taking their Organic chemistry classes with accompanying grades tracked over time to test the effectiveness of the different case comparison conditions used in a real world setting. The goal of this current project was to observe the application of the science behind case comparisons which has been shown to be successful in a host of other fields of learning to an entirely new field (Organic Chemistry); which tends to present many challenges to the college student population. Being a field of study that showcases lots of patterned trends, learning could potentially be improved by the prior presentation of well-matched examples that attempt to highlight the concept being taught.

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