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Implementation and Student Testing of a Web-Based, Student-Centered Stereochemistry Tutorial

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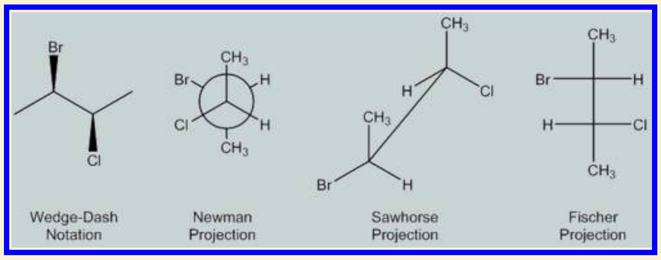
Ⓢ *Supporting Information*

ABSTRACT: The implementation of a web-based stereochemistry tutorial, which allows students to select their preferred structural representation and method for making stereochemical comparisons between molecules, is discussed. The tutorial was evaluated by students in three different introductory organic chemistry courses at a large midwestern university. The data show that students did use a variety of different methods for making stereochemical comparisons between molecules and that prior exposure to lectures on stereochemistry by the course professor strongly influenced these choices. Furthermore, the level of improvement in stereochemical knowledge as a result of using only the tutorial was comparable to, or higher than, that achieved by students who were only exposed to lectures by the course professor, regardless of the method chosen for making stereochemical comparisons between molecules.



KEYWORDS: *Second-Year Undergraduate, Organic Chemistry, Internet/Web-Based Learning, Stereochemistry, Student-Centered Learning*

■ INTRODUCTION

The ability to correctly interpret the structural information in a molecule is critical to success in an organic chemistry course, as this skill is required for nearly all aspects of organic chemistry, including conformational analysis, stereochemistry, and the completion of chemical reactions.[1] However, students often struggle with the interpretation of molecular structures, particularly in stereochemical contexts, because most molecules are represented using two-dimensional structures, such as drawings or digital images.[1−8] While research has shown that student performance involving structural interpretation is improved when physical models are utilized,[1,2] such models are not extensively incorporated into organic chemistry courses, as their construction can be time-consuming and spatially cumbersome, particularly as molecular size increases. Consequently, two-dimensional representations are more commonly used in organic chemistry courses.

However, not all students are able to successfully interpret two-dimensional drawings.[1,2,9−11] This challenge is compounded by the variety and relative clarity of structural representations that exist for two-dimensional drawings.[2] Some molecular representations, such as Fischer and Haworth projections, which are generally introduced simultaneously with stereochemistry, are abstract and do not clearly represent the spatial orientation or bond angles within a molecule.[1] When students are presented with new information that does not easily integrate into their pre-existing knowledge, they will often attempt to reinterpret this information using a more familiar context.[12−14] Consequently, many students will attempt to translate unfamiliar structural drawings into other, more preferable, representations. Unfortunately, the process for successfully completing this conversion step is not often emphasized in organic chemistry lectures or textbooks. Therefore, attempting such translations introduces the potential for additional errors, which can ultimately cause the reinterpretation process to fail.[1,9−11] Because of these factors, the challenge of correctly interpreting two-dimensional molecular structures in the context of larger problems is daunting and, when done incorrectly, can often result in a loss of credit on graded work, even when the underlying content itself is well-understood.[1,14]

Despite extensive research delineating the problem, there is a surprising lack of instructional tools that address these challenges. To fill this void, a web-based, student-centered stereochemistry tutorial has been created. This tutorial introduces students to all of the two-dimensional structural representations for molecules, in parallel, allows them to select a representation that best integrates into their pre-existing knowledge and visuospatial preferences, and provides instructions on how to reinterpret less familiar representations in the chosen depiction. The development and generation of this tool have been discussed in a previous paper,[15] and the finalized version, entitled Stereochemistry Tutorial, can now be found on the Chemical Education Digital Library (ChemEd DL).[16] It is a free, open-access tool for any student, teacher, or otherwise-interested person to use.

To determine the validity of this tutorial as a pedagogical tool, three different evaluations were done over the course of several

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Scheme 1. Timeline for the Activities Conducted during the Third Student Trial of the Stereochemistry Tutorial

Date	Activities
September 5 (Day 1)	- Consent forms distributed/collected - All students completed the Stereochemistry Pre-Test - Tutorial Only Group obtained tutorial access
September 19 (Day 15)	- Control and Tutorial Only Groups completed Stereochemistry Post-Test - Tutorial Only Group turned in Attitudinal Survey
October 6 (Day 32)	Approximate start date of in-class stereochemistry lectures (given by the course professor)
October 17 (Day 43)	- Lecture Only Group completed Stereochemistry Post-Test - Control and Lecture Only Groups obtained tutorial access (All students now have tutorial access)
October 31 (Day 57)	Control and Lecture Only Groups turned in Attitudinal Survey
November 20 (Day 77)	All students completed the in-class examination for credit (covering stereochemistry)

semesters. This paper describes the assessment tools used in these studies, as well as the results obtained. Since the third study was the most comprehensive and final trial, those results are the primary focus of this paper. The information for the first two trials is available from the authors, upon request.

SURVEYS USED IN EVALUATING THE STEREOCHEMISTRY TUTORIAL

Both an attitudinal survey and a stereochemistry quiz were used to evaluate this stereochemistry tutorial. Both the attitudinal survey and the stereochemistry quizzes were presented to the students in a pencil-and-paper format and are reproduced in the Supporting Information. The purpose of the stereochemistry quizzes was to determine the student's gain in knowledge after being exposed to instruction, either in class or from the tutorial, on the topic of stereochemistry. Additionally, the use of an attitudinal survey enabled the authors to collect student-identified responses relating to the method used for determining the stereochemical relationship between molecules and other qualitative feedback. The stereochemistry quizzes were administered in a pre- and post-test fashion and were vetted by a faculty member who was an experienced teacher of organic stereochemistry. The content of the questions on all pre- and post-test surveys was identical.

IMPLEMENTATION OF THE STEREOCHEMISTRY TUTORIAL

The tutorial was used by students enrolled in four specific lecture sections of CHEM 341 and CHEM 343, which are introductory organic chemistry courses, over the course of three semesters. CHEM 341 is a one-semester overview of "essential" organic chemistry topics, which entails brief exposure to a wide range of reactions involving a variety of functional groups. Students enrolled in CHEM 341 are usually majoring in life science programs such as botany, agriculture, or clinical laboratory science. CHEM 343 is the first semester of a two-semester sequence (CHEM 343, CHEM 345) of organic chemistry. CHEM 343 and CHEM 345 expose students to the same reactions that are discussed in CHEM 341 in much greater detail. Students enrolled in CHEM 343 are usually chemistry, biology, or physics majors or are involved in one of the pre-professional programs (pre-medical, pre-pharmacy, pre-dental).

Approximately 500 students enrolled in two sections of CHEM 343 were invited to participate in the study; both sections were taught by the same professor. Involving two sections allowed for a larger number of potential participants. Additionally, because both sections were taught by the same instructor, essentially the same in-class lectures were presented to all students. Trial 3 assessed the tutorial using both the attitudinal survey and the stereochemistry quizzes, which allowed for the combination of the two data sets. This enabled the effectiveness of the tutorial to be gauged with respect to several factors, such as the amount of time spent on the tutorial or the method used for determining the stereochemical relationship between molecules.

The students were randomly assigned to one of three study groups. Each group was assigned a different schedule for completing the tutorial, the attitudinal survey, and the stereochemistry post-test. All groups had access to all activities prior to the date of the in-class examination on stereochemistry. This schedule was detailed in each of three study group assignment sheets, which were stapled to a consent form; these forms were then randomly distributed to the students. The consent form, as well as all three study group assignment sheets, is reproduced in the Supporting Information.

This was a blind study. To minimize the possibility of bias, the researcher who graded the stereochemistry quizzes did not know which study participation code correlated with which study group and which surveys were pre-tests and which were post-tests. To enable this blind format, a chemistry graduate student who was not otherwise involved with the research study assigned the first number (1, 2, or 3) of the four-digit study participation code to each study group and then wrote the study participation codes on the corresponding consent forms. These

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Table 1. Summary of Data and Statistical Significance Results for Mean Pre- to Post-Test Differences Based on Study Group

Study Group	Number of Participants	Mean Pre-Test Score[a]	Mean Post-Test Score[a]	Mean Difference (Between Pre- and Post-Test Scores)	ρ Value (Within Group)	Cohen's d Effect Size
Control	116	1.353	1.940	0.586	0.006	0.42
Lecture Only	126	1.421	5.778	4.357	<0.001	2.63
Tutorial Only	102	1.451	5.716	4.265	<0.001	2.51

[a]Note: There was a maximum of 17 points possible on the pre- and post-tests.

assignments were kept private until after all stereochemistry quizzes were graded.

All students participating in the research study were asked to take both a pre-test and a post-test, work through this stereochemistry tutorial, and complete the attitudinal survey evaluating this tutorial. Completion of each of these four activities was worth five points of course credit, for a maximum of 20 points possible per student. Students could do any combination of these activities for course credit, regardless of whether they chose to participate in the research study. Because of the assignment of course credit for each of these activities, we made certain that every student had the opportunity to complete all four activities. The three study groups differed by what the students were asked to do before taking their post-tests:

(i) Control Group: Students did not have access to either the tutorial or to in-class lectures on stereochemistry before taking the post-test.
(ii) Tutorial Only Group: Students had access to the tutorial but did not have access to in-class lectures on stereochemistry before taking the post-test.
(iii) Lecture Only Group: Students did not have access to the tutorial but did have access to in-class lectures on stereochemistry before taking the post-test.

The timeline for the activities is detailed in Scheme 1.

All students were given access to both the tutorial and to the in-class lectures before any in-class assessment (examination involving stereochemistry) for course credit. This allowed all students to have an equal advantage on any in-class assessment for credit. For a student to be deemed a valid study participant, all four activities needed to be completed. Also, students who spent less than 50 minutes working through the tutorial (a time period equivalent to one in-class lecture period) or viewed fewer than 35 pages (approximately 10% of the total page count of the tutorial) were not deemed valid study participants. This decision was made based on statistical analysis, which is detailed in a later section of this article.

Students were able to log in to the tutorial using an assigned username (their study participation code) and password, which each student was then able to reset to a unique password. The administrative page of the tutorial recorded the number of times each participant accessed the tutorial, as well as the number of pages of the tutorial each participant viewed and the number of minutes each participant spent working through the tutorial. At the end of each relevant portion of the study, this administrative page was accessed by a graduate student who was not otherwise involved in the research study to record the values for all of these quantities for each study participant.

After all activities had been completed, the stereochemistry quizzes were graded, and the information on the attitudinal surveys was recorded. Only after that were the identities of the pre-tests and post-tests revealed to the researcher. Statistical analyses were then performed, after which the study group to which each numerical code was assigned was disclosed to the researcher. The free-response answers provided by students on the attitudinal survey were recorded and utilized to draw general conclusions about student perceptions of the stereochemistry tutorial.

■ DATA ANALYSIS

Quantitative data, in the form of pre- and post-tests, were scored out of a total of 17 points. Once all pre- and post-tests were scored, point totals were recorded in Microsoft Excel. Data submitted by the students on the attitudinal survey were also recorded in Microsoft Excel. Data regarding the methods that students used for determining the stereochemical relationships between both acyclic and cyclic molecules and the amount of time each student spent working on the tutorial (as recorded on the administrative page of the tutorial) were numerically coded, such that this information could be used as a factor for subsequent statistical analysis.

Based on the criteria for participant validity, there were 345 valid student participants for this trial. Qualitative and quantitative data for these students were then transferred to SPSS 16.0[17] for statistical analysis. Data in SPSS were categorized by student and included the study group to which each was assigned (Control, Lecture Only, or Tutorial Only), amount of time spent working through the tutorial, student-reported method for determining stereochemical relationships between acyclic molecules, student-reported method for determining stereochemical relationships between cyclic molecules, and pre- and post-test scores. Comparisons between the sub-groups of each of these listed categories were made using an independent-groups one-way analysis of variance (ANOVA). Comparisons between any two of these listed categories with respect to pre- and post-test scores were made using the general linear model repeated measures ANOVA. All analyses were done at the 95% confidence interval. The results of these statistical analyses, as well as some of the raw data, were organized using tables, bar graphs, and scatter plots, some of which were fitted using linear equations. Key data are reproduced and discussed in the following paragraphs.

Before any comparison could be made between the pre- and post-test score differences between any of the study groups, it had to be determined that there was no difference in the initial stereochemical aptitude of the students in any particular study group relative to the others. Among the 47 comparisons made regarding the pre-test data, there were only six statistically significant differences in the pre-test scores of the students. Because the students were randomly assigned into each of the three study groups, and the students themselves dictated the amount of time they spent working through the tutorial and which method for determining stereochemical relationships they utilized, the data can be considered highly randomized. Therefore, it is reasonable to conclude that student participants

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had the same initial knowledge of stereochemistry and to compare improvements from pre-test to post-test score among the groups.

Analyses were then done to determine whether there were changes in the pre- and post-test scores based on study group, minutes spent working on the tutorial, and method chosen for determining the stereochemical relationship between acyclic and cyclic molecules. The initial comparisons were made among the three study groups.

Data involving the mean pre-test and post-test scores of students in each of the three study groups are shown in Table 1. Statistical analyses were done to determine whether the increases from pre-test to post-test were significant at the 95% confidence interval. The null hypotheses that there was no difference between the pre- and post-test scores of the students in the Control Group ($\rho = 0.006$), Lecture Only Group ($\rho < 0.001$), and Tutorial Only Group ($\rho < 0.001$) were all rejected. Therefore, the improvements from pre- to post-test of all of these groups are statistically significant. Furthermore, the values of Cohen's d for the Lecture Only Group and the Tutorial Only Group were very large, which indicates that there was a substantially significant improvement from pre- to post-test for these two groups.

The next analyses done were to determine whether there were changes in the pre- and post-test scores based on minutes spent working on the tutorial. Fifty-minute intervals were chosen because one course lecture period was fifty minutes long. Approximately four course lectures were devoted to stereochemistry. Mean pre- and post-test scores, categorized by minutes spent working on the tutorial, are shown in Table 2. A plot of the mean difference between the pre- and post-test scores, categorized by minutes spent working on the tutorial, is shown in Figure 1. Statistical analyses were done to determine whether these increases were significant at the 95% confidence interval. The null hypotheses that there was no difference between the pre- and post-test scores of the students in the each of the sub-groups were all rejected. Therefore, the improvements from pre- to post-test of all of these groups are statistically significant.

Table 2. Summary of Data and Statistical Significance Results for Mean Pre- to Post-Test Differences of the Tutorial Only Group Based on Minutes Spent on the Tutorial.

Minutes Spent on Tutorial	Number of Participants	Mean Pre-Test Score[a]	Mean Post-Test Score[a]	Mean Difference (Between Pre- and Post-Test Scores)	ρ Value (Within Group)
1−50[b]	40	0.825	2.275	1.450	<0.001
51−100	30	1.567	4.200	2.633	<0.001
101−150	30	1.733	5.200	3.467	<0.001
151−200	18	1.222	5.889	4.667	<0.001
201−250	9	0.889	5.667	4.778	0.005
251−300	7	1.286	8.143	6.857	0.001
301+	9	1.222	9.889	8.667	<0.001

[a]Notes: There was a maximum of 17 points possible on the pre- and post-tests. [b]The 40 participants who spent between 1 and 50 minutes on the tutorial were not considered to be valid Tutorial Only Group participants, and their data were therefore not included in any other calculations.

Next, statistical analyses were done to determine whether the improvements shown in the sub-groups of the Tutorial Only Group, based on minutes spent working on the tutorial, were statistically different from the improvements shown in the other time-based sub-groups. Results of these statistical analyses are shown in Table 3. These data show that, based on minutes working on the tutorial, there was no statistically significant difference ($\rho > 0.05$) between the improvements of the students in each sub-group of the Tutorial Only Group and the sub-group directly previous to it (in which less time was spent working on the tutorial). An exception to this was found when comparing the 51−100 minute sub-group with the 1−50 minute sub-group. The last column in Table 4 shows that there was a significant difference between the 1−50 minute sub-group and all of the other sub-groups. Therefore, the improvement shown by the 1−50 minute sub-group is different, statistically, from the improvements shown by each of the other sub-groups.

Subsequently, statistical analyses were done to determine whether the improvement shown in the sub-groups of the Tutorial Only Group, based on minutes spent working on the tutorial, were statistically different from the improvement shown in Lecture Only Group. Results of these statistical analyses are shown in Table 4. These data show that there was a statistically significant difference between the improvements of the students in each sub-group of the Tutorial Only Group, based on minutes spent working on the tutorial, and the students in the Lecture Only Group for several of the data sets. For the 1−50 minute and 51−100 minute sub-groups, this difference was in favor of the Lecture Only Group; for the 251−300 minute and 301+ minute sub-groups, this difference was in favor of the Tutorial Only Group. There was no statistically significant difference between the improvements for the remaining sub-groups.

Following these time-based analyses, analyses were done to determine whether there were changes in the pre- and post-test scores based on which method was chosen for determining stereochemical relationships between acyclic molecules. A plot of mean pre- and post-test scores, categorized by method chosen for determining stereochemical relationships between acyclic molecules, is shown in Figure 2. It is visually apparent that all of the groups increased their scores from pre- to post-test. Statistical analyses were done to determine whether these increases were significant at the 95% confidence interval. Results of these statistical analyses are shown in Table 5. These data show that the improvements from pre- to post-test scores of the students in the *R* and *S* Method, Wedge-Dash Notation Method, and Sawhorse Projection Method sub-groups are statistically significant and that the corresponding differences of the students in the Newman Projection Method and Fischer Projection Method sub-groups are not statistically significant. Similar results were obtained when analyses were done for methods for determining stereochemical relationships between cyclic molecules.

Next, we explored whether the improvement shown in the sub-groups of the Tutorial Only Group, based on method chosen for determining the stereochemical relationship between acyclic molecules, was statistically different from the improvements shown in the other method-based sub-groups for acyclic molecules. Results of these statistical analyses are shown in Table 6. These data show that there was no statistically significant difference ($\rho > 0.05$) between the improvements of the students in each sub-group of the Tutorial Only Group, based on method chosen for determining the stereochemical relationship between acyclic molecules and each of the other similarly categorized sub-groups, with the exception of the comparison between the Wedge-Dash Method and Fischer Projection Method sub-groups ($\rho = 0.048$). Similar results were

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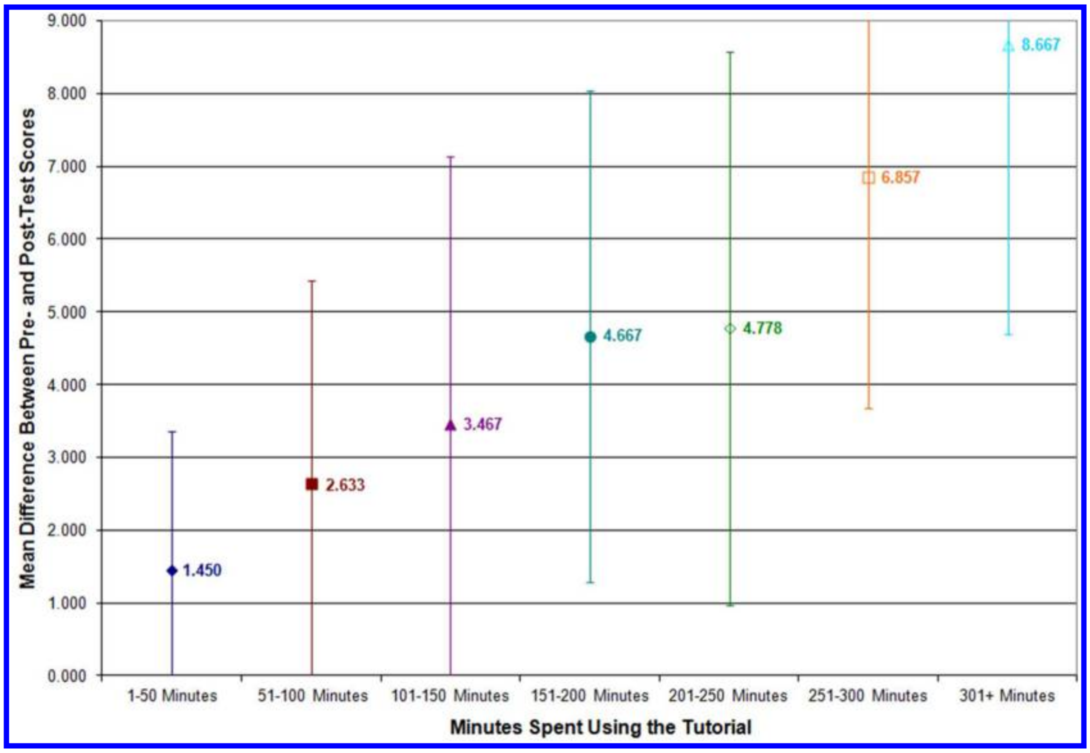

Figure 1. Plot of the mean difference between pre- and post-test scores of sub-groups of the Tutorial Only Group based on minutes spent on the tutorial. There was a maximum of 17 points possible on the pre- and post-tests. The error bars correspond to one standard deviation.

Table 3. Summary of Data and Statistical Significance Results for Mean Pre- to Post-Test Differences of the Tutorial Only Group Based on Minutes Spent on the Tutorial

Minutes Spent on Tutorial	Number of Participants	Mean Difference (Between Pre- and Post-Test Scores)[a]	ρ Value (Between Group and Previous Group)	ρ Value (Between Group and 1−50 Minutes Spent Group)
1−50[b]	40	1.450		
51−100	30	2.633	0.039	0.039
101−150	30	3.467	0.327	0.004
151−200	18	4.667	0.265	<0.001
201−250	9	4.778	0.939	<0.001
251−300	7	6.857	0.265	<0.001
301+	9	8.667	0.342	<0.001

[a]Notes: There was a maximum of 17 points possible on the pre- and post-tests. [b]The 40 participants who spent between 1 and 50 minutes on the tutorial were not considered to be valid Tutorial Only Group participants, and their data were therefore not included in any other calculations.

Table 4. Summary of Data and Statistical Significance Results for Mean Pre- to Post-Test Differences of the Tutorial Only Group Based on Minutes Spent on the Tutorial Relative to the Lecture Only Group

Minutes Spent on Tutorial	Number of Participants	Mean Difference (Between Pre- and Post-Test Scores)[a]	ρ Value (Between the Tutorial Only Group and Lecture Only Group)	Group with Higher Improvement
Lecture Only	126	4.357		N/A[c]
1−50[b]	40	1.450	<0.001	Lecture Only Group
51−100	30	2.633	0.005	Lecture Only Group
101−150	30	3.467	0.165	No Difference
151−200	18	4.667	0.688	No Difference
201−250	9	4.778	0.691	No Difference
251−300	7	6.857	0.035	251−300 minutes (Tutorial Only Group)
301+	9	8.667	<0.001	301+ minutes (Tutorial Only Group)

[a]Note: There was a maximum of 17 points possible on the pre- and post-tests. [b]The 40 participants who spent between 1 and 50 minutes on the tutorial were not considered to be valid Tutorial Only Group participants, and their data were therefore not included in any other calculations. [c]N/A: Not applicable.

obtained when analyses were done for methods for determining stereochemical relationships between cyclic molecules.

Four key sets of qualitative data also are reproduced and discussed in the following paragraphs. The qualitative goals of

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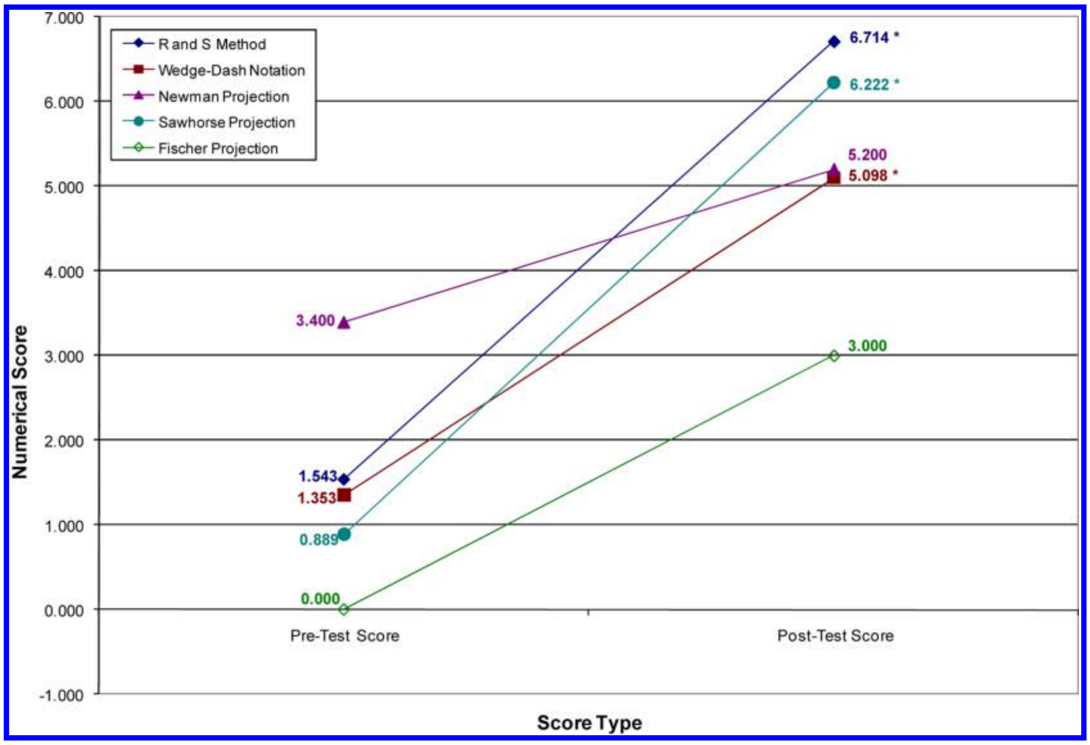

Figure 2. Plot of the mean pre- and post-test scores of sub-groups of the Tutorial Only Group based on the method chosen for determining stereochemical relationships between acyclic molecules. There was a maximum of 17 points possible on the pre- and post-tests. An asterisk (∗) indicates that the difference between the pre- and post-test scores for that study group is statistically significant.

Table 5. Summary of Data and Statistical Significance Results for Mean Pre- to Post-Test Differences of the Tutorial Only Group Based on the Method Chosen for Determining the Stereochemical Relationship between Acyclic Molecules

Method for Acyclic Determination	Number of Participants	Mean Pre-Test Score[a]	Mean Post-Test Score[a]	Mean Difference (Between Pre- and Post-Test Scores)	ρ Value (Within Group)
R and *S* Method	35	1.543	6.714	5.171	<0.001
Wedge-Dash Notation Method	51	1.353	5.098	3.745	<0.001
Newman Projection Method	5	3.400	5.200	1.800	0.255
Sawhorse Projection Method	9	0.889	6.222	5.333	0.001
Fischer Projection Method	2	0.000	3.000	3.000	0.374

[a]Note: There was a maximum of 17 points possible on the pre- and post-tests.

Table 6. Summary of Data and Statistical Significance Results for Mean Pre- to Post-Test Differences of the Tutorial Only Group Based on the Method Chosen for Determining the Stereochemical Relationship between Acyclic Molecules Relative to the Other Method-Based Sub-Groups for Acyclic Molecules

Method for Acyclic Determination	Number of Participants	Mean Difference (Between Pre- and Post-Test Scores)[a]	ρ Value (Between Group and *R* and *S* Group)	ρ Value (Between Group and Wedge-Dash Group)	ρ Value (Between Group and Newman Group)	ρ Value (Between Group and Sawhorse Group)
R And *S* Method	35	5.171				
Wedge-Dash Notation Method	51	3.745	0.094			
Newman Projection Method	5	1.800	0.096	0.240		
Sawhorse Projection Method	9	5.333	0.915	0.207	0.051	
Fischer Projection Method	2	3.000	0.482	0.048	0.652	0.325

[a]Note: There was a maximum of 17 points possible on the pre- and post-tests.

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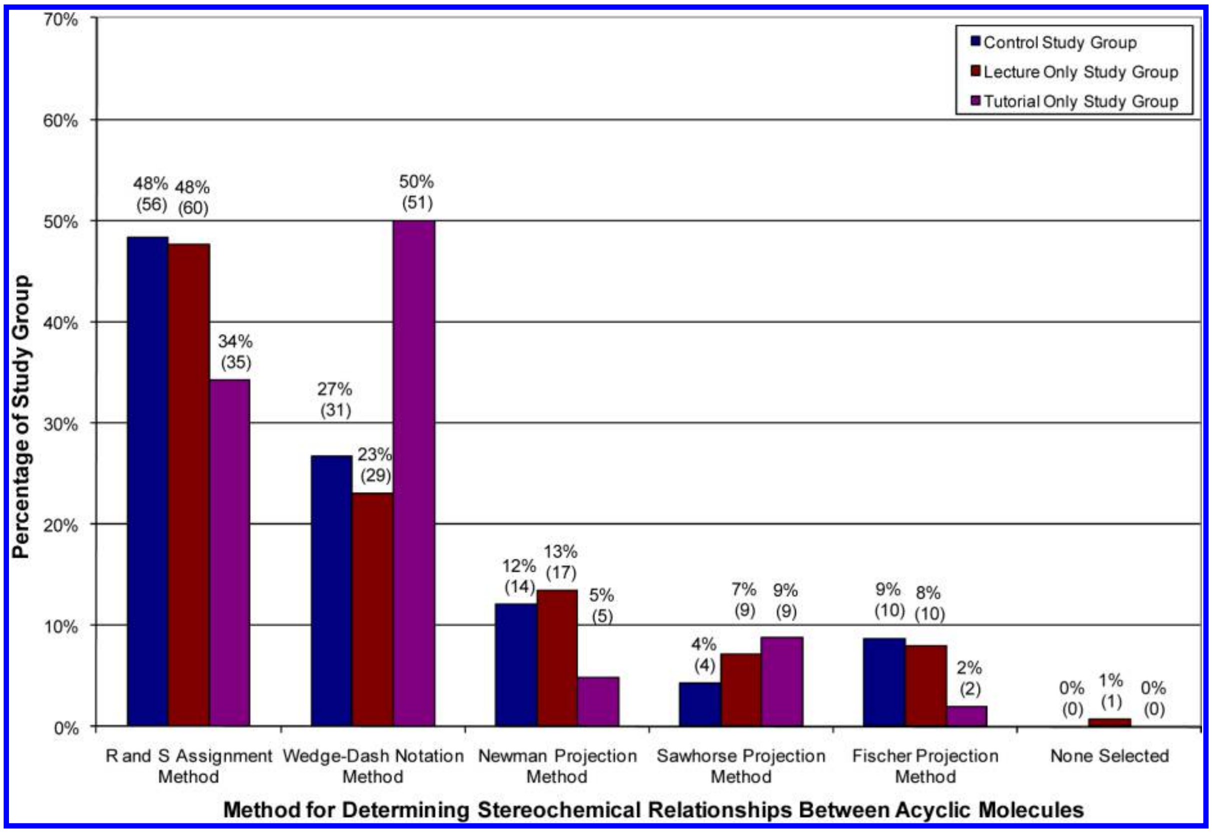

Figure 3. Graph summarizing student responses to Question 4 on the attitudinal survey: "Which method for Determining Stereochemical Relationships between molecules did you use for *acyclic* molecules? Please circle one."

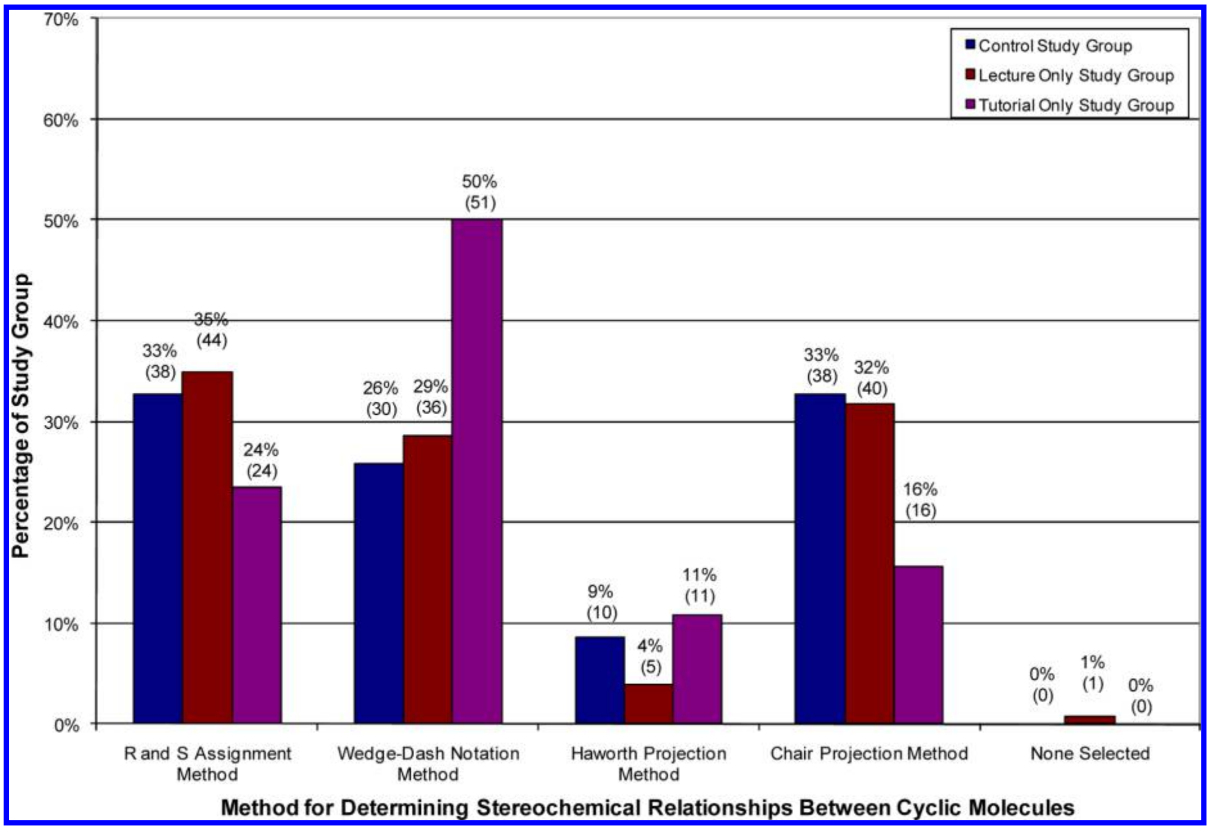

Figure 4. Graph summarizing student responses to Question 5 on the attitudinal survey: "Which method for Determining Stereochemical Relationships between molecules did you for *cyclic* molecules? Please circle one."

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this trial were to determine whether students would find the tutorial a useful tool and whether students would use a variety of methods for determining the stereochemical relationship between molecules. Students in each of the three study groups did use a variety of methods for determining the stereochemical relationship between acyclic molecules (Figure 3) and cyclic molecules (Figure 4). Furthermore, a large majority of students had a positive impression of the tutorial (Table 7) and would be likely to recommend the tutorial as a tool for students in a similar course (Table 8).

Table 7. Summary of Student Responses to Question 12 on the Attitudinal Survey[a]

Rating	Control Study Group	Lecture Only Study Group	Tutorial Only Study Group
Excellent	19 (16%)	30 (24%)	19 (19%)
Very good	71 (61%)	73 (58%)	59 (58%)
Good	23 (20%)	20 (16%)	18 (18%)
Fair	2 (2%)	3 (2%)	5 (5%)
Poor	1 (1%)	0 (0%)	1 (1%)

[a]Note: Question 12 on the Attitudinal Survey reads, "What was your overall impression of the Stereochemistry Tutorial? Please circle one and explain your answer. Try to be specific in describing aspects of the tutorial that were positive and aspects of the tutorial that could be improved."

Table 8. Summary of Student Responses to Question 13 on the Attitudinal Survey[a]

Recommendation	Control Study Group	Lecture Only Study Group	Tutorial Only Study Group
Yes	113 (97%)	124 (98%)	95 (93%)
No	3 (3%)	2 (2%)	7 (7%)

[a]Note: Question 13 on the Attitudinal Survey reads, "Would you recommend this Stereochemistry Tutorial to another person taking an introductory organic chemistry course? Please circle one."

■ DISCUSSION OF RESULTS

Statistical analyses showed that all three study groups improved from pre- to post-test. Upon first consideration, this result is disconcerting for the Control Group. However, upon further reflection, it is reasonable that there was a slight increase in scores from pre- to post-test in the Control Group. Although students in this group were not exposed to any stereochemical content between their pre- and post-tests, they were introduced to a few core chemical concepts, such as chemical nomenclature and interpreting and understanding accepted structural conventions, such as bond-line formulas. At the time of the pre-test, the second class day of the semester, none of this content had been presented. This increase in knowledge of structural notation could allow students to better interpret the structural content on the post-test, which provides a reasonable explanation for the mean 0.6 point (out of 17) increase of this group. It is of note that the students in both the Tutorial Only and the Lecture Only Groups also had exposure to core chemical concepts between the dates of their pre- and post-tests, which would cause a similar increase in scores from pre- to post-test. However, since the Lecture Only Group had even more class periods in which to be exposed to these concepts between their pre- and post-tests, it could be argued that the increase in performance of this group was more greatly impacted by their time spent in class, which further strengthens the conclusion that the Tutorial Only Group performed as well as the Lecture Only Group. Finally, this conclusion is supported by the Cohen's d values, shown in Table 1, for each of the three study groups. The effect size of the Control Group is quite small (0.42) in comparison to the Lecture Only Group (2.63) and Tutorial Only Group (2.51). Even if the value of the effect size of the Control Group were to be subtracted from those of the two treatment groups, the effect size value of both treatment groups is still substantial.

Statistically significant improvements from pre- to post-test scores in both of the treatment groups, regardless of whether the students worked through the tutorial or attended course lectures by the professor, were very positive results. The data from this trial support the conclusion that students working through the tutorial can effectively learn stereochemical concepts. An additional important result arose from this quantitative information. For the Tutorial Only Group, the mean improvements in score from pre-test to post-test were essentially the same as those of the Lecture Only Group. This outcome allows for a preliminary statement that the tutorial could be as effective, instructionally, as the lectures given by the course's professor.

Statistically significant improvements from pre- to post-test of all of the time-based sub-groups of the Tutorial Only Groups were also positive results. It was also very encouraging that student improvement did not plateau at any point. The strong linear correlation between improvement and minutes spent working on the tutorial provides solid support for the tutorial's effectiveness as a teaching tool. This result is somewhat expected, as "time on-task" usually enhances performance on an activity.[18]

Additionally, these data support the decision to discard the data from those participants who spent less than 51 minutes working on the tutorial. When considering each time-based sub-group sequentially, the only sub-group where improvement was statistically different from the subsequent group was the 1−50 minute sub-group. Also, the improvement of the 1−50 minute sub-group was statistically different from all of the other time-based sub-groups, which had statistically similar improvements. Therefore, it was reasonable to consider the 1−50 minute sub-group as distinct from the others and exclude it from the set of valid Tutorial Only Group participants for other analyses.

It was also interesting to consider the effectiveness of the tutorial, relative to the course lectures, based on how much time was spent working on the tutorial. There were approximately four course lectures, or roughly 200 minutes, devoted to discussing stereochemistry. The amount of additional time students spent reading the textbook or working on homework problems was variable, and the corresponding data were not collected in this study. It was recommended that students spend at least an equal amount of time out of class, relative to in-class time, on self-studying a topic. Therefore, it is reasonable to conclude that students in the Lecture Only Group spent between 200 and 400 minutes studying stereochemistry.

In light of this time-based information, when comparisons are made between the Lecture Only Group and the time-based sub-groups of the Tutorial Only Group, it is not surprising that the improvements made by the Lecture Only Group were statistically greater than those in the Tutorial Only Group who spent 100 minutes or less working on the tutorial. It is also not unexpected that there was no statistical difference in the improvement made by the Lecture Only Group and those in the Tutorial Only Group who spent between 101 and 250 minutes working on the tutorial. However, those who spent more than

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251 minutes working on the tutorial had an improvement statistically superior to those in the Lecture Only Group. Although it would be over-reaching to conclude that working with the tutorial for more than 251 minutes would be more effective than attending course lectures, it is highly encouraging to see that students spending reasonable amounts of time with the tutorial made improvements competitive with those attending lectures given by the course professor.

The final analyses considered the distribution of methods that students selected for determining the stereochemical relationship between both acyclic and cyclic molecules and whether pre- to post-test improvement depended on which method was selected. The large range of methods that students selected was an interesting result, particularly because a significant portion of students selected "non-traditional" methods for making molecular comparisons. This supports the hypothesis that many students prefer to visualize molecules and make molecular comparisons using methods that usually are not presented in textbooks.

Moreover, it is interesting to observe the divergence in student selection based on whether the tutorial was viewed before (Tutorial Only Group) or after (Lecture Only Group and Control Group) lectures were given by the course's professor. Not surprisingly, the students who viewed the tutorial after the corresponding course lectures primarily selected methods that were most consistent with what had been discussed in class. The selections made by the students in the Tutorial Only Group were dissimilar to those of the other two groups, sometimes drastically so. The contrast in student selection, relative to whether the student was initially exposed to stereochemistry through the tutorial or the course lectures, quite clearly shows the impact a course professor can have on the way students look at the content being presented to them. However, a significant portion of students who viewed the tutorial after attending in-class lectures still opted to select methods for determining the stereochemical relationships between molecules that were different from what was presented in class. That these students diverged from what was presented in class indicates that they likely did not strongly relate to the course professor's chosen presentation, which further supports the conclusions drawn above.

Because one of the primary goals for developing this tutorial was to allow students to choose a preferred method for determining the stereochemical relationship between molecules, the variance in student selections was highly important. However, had there not been significant improvement and equivalency of improvement in student learning, regardless of which method was chosen for making these molecular comparisons, the ability to individualize student visualization would have been instructionally irrelevant.

The statistical data presented previously show that, with two exceptions (Fischer Projection Method Group and Newman Projection Method Sub-Group), all sub-groups, based on visualization method chosen, did improve statistically from pre- to post-test. These exceptions may be due to the small sample populations of these sub-groups and the unusually high mean pre-test score of the Newman Projection Method Group. Furthermore, all sub-groups, based on visualization method chosen, showed a statistical equivalency in improvement, except in one case (the comparison between the Wedge-Dash Method and Fischer Projection Method Sub-Groups). This discrepancy can again likely be explained by the small sample population in the Fischer Projection Method Group. The overall improvement from pre- to post-test and the statistical similarity of the extent of these improvements strongly support the conclusion that individualizing student learning in this tutorial is highly successful. All of the quantitative results discussed above provide strong evidence that this stereochemical tutorial is an effective teaching tool.

The attitudinal feedback provided by students was also encouraging. There is overwhelming evidence that a majority of students had a favorable overall impression of the tutorial and that they would recommend the tutorial as a tool for students in a similar course.

■ SUMMARY

We have shown that working through the stereochemistry tutorial without course lectures on stereochemistry resulted in a statistically significant improvement from pre- to post-test and that this improvement was comparable to an improvement shown by students who attended in-class lectures on stereochemistry. Furthermore, the extent of this improvement did not depend on which method students used for determining the stereochemical relationships between molecules. Students did show variance in which method they used for determining the stereochemical relationship between molecules, and these choices seemed to be influenced by the ways in which the course professor presented analogous material. Overall, the student response to using the tutorial was favorable. The combination of these quantitative and qualitative results strongly indicates that this stereochemistry tutorial is a pedagogically sound tool that can be successfully used for individualized student learning of stereochemical concepts.

■ FUTURE RESEARCH

Since the tutorial has been shown to be effective for teaching stereochemistry and is now available for anyone to use, it would make an excellent instrument for future research centered on student learning styles. Learning styles indicate a tendency to favor a particular sensory (visual/spatial, auditory, or kinesthetic/physical) or cooperative (social/interpersonal or solitary/intrapersonal) strategy for learning and recalling information.[19−21] It would be interesting to explore the extent to which the learning styles of students influenced their use of the tutorial, particularly regarding which methods the students chose for determining the stereochemical relationships between molecules. The majority of the methods presented in the tutorial allowed students to make side-by-side comparisons of molecules, an approach that would likely appeal more to visual learners. It would also be of interest to obtain data about whether the learning styles of students impacted student preferences to learn about stereochemistry by working through the tutorial (visual/solitary), reading the course textbook (visual/solitary), attending course lectures (auditory/social), or working in groups with other students (auditory/social). Since one of the primary reasons for developing this tutorial was to create a tool geared toward individual visualization methods, conducting future research to determine which students and student learning styles were most impacted is a worthwhile pursuit.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Description and content of the attitudinal survey; content and question vetting of the stereochemistry quiz; consent form and study group assignment sheets. This material is available via the Internet at http://pubs.acs.org.

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Notes

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