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Chemical Education Research

"What About the Students Who Switched Course Type?": An Investigation of Inconsistent Course Experience

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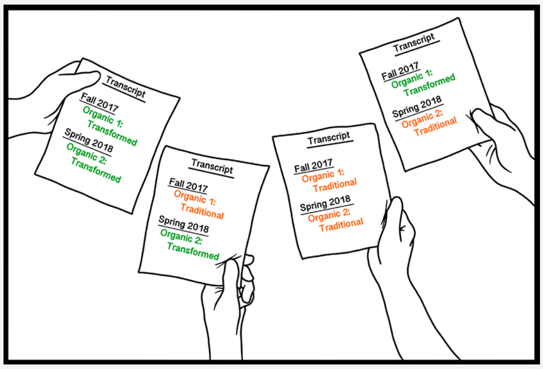
ABSTRACT: Students typically experience a sequence of required courses. These courses are generally taught by different instructors with different pedagogical strategies and in some cases different emphases on what students should know and how they should know it. However, there are few published studies on the impact of the switching course type on learning outcomes. In this report, we use a unique research opportunity that allows us to investigate a two-semester course sequence in organic chemistry where both traditional and transformed courses were taught. We followed students over two semesters in both the transformed and traditional courses to characterize (1) students' use of mechanistic arrows to predict products and (2) how students constructed causal mechanistic explanations for simple S_N2 reactions. Here, we report how students who switched course type from the first to the second semester accomplished these tasks compared with their peers who took the same approach for both semesters. At the end of the course sequence, we find that students who switched course type performed similarly to their peers in the course type into which they switched. In particular, students' use of arrow pushing and mechanistic reasoning decreases when they switch from a transformed course where mechanistic reasoning is emphasized compared to the more traditional course. It appears that students adapt to the course culture and assessment strategies used in each course type, resulting in an apparent loss of learning gains associated with the transformed course. This suggests that systemic change cannot be accomplished in a fragmentary fashion; a more coordinated and coherent approach is necessary if improved learning outcomes are to be attained and reinforced.



KEYWORDS: *Organic Chemistry, Chemical Education Research, Mechanisms of Reactions, Second-Year Undergraduate*

■ INTRODUCTION

Driven by calls to action,[1] funding agencies' priorities,[2] evidence about what and how students are learning,[1,3] and calls for more equitable approaches to learning,[4,5] the impetus to transform higher education STEM teaching and learning has become increasingly urgent. Proposed improvements have ranged from relatively minor add-ons, such as technology-based tutorials designed to improve particular skills,[6−8] to changes in pedagogy that engage students in their learning[9−15] to whole course and curricular transformations that may incorporate all of these mechanisms for improvement.[16−19] In some cases, there have been demonstrated improvements in overall grades and in students' ability to construct explanations and models.[16,19,20] However, despite all the resources and evidence to support various transformations, studies show that the uptake of these approaches has been slow: traditional lecture is still the predominant mode of instruction for most higher education STEM courses,[21] and students are rarely called upon to use their knowledge to model, predict, or explain phenomena either during instruction or on course assessments.[22]

Certainly, there are many reasons for the glacial pace of change, including that the typical faculty reward structure is not designed to address instructional excellence, that there remains a satisfaction with the status quo, and that there is an inconsistent approach to how meaningful change can be incentivized, recognized, and sustained. Indeed, much of the research on change in higher education points to the need for an integrated approach in which researchers, practitioners, administrators, and faculty developers all contribute to the proposed transformation, and that a culture that rewards teaching is promoted.[23−25] Lone faculty, however promising their instructional transformations, may have difficulties in accomplishing systemic change.[26,27]

In this light, it is important to recognize that while there are many ongoing individual initiatives, systemic reforms and research on their impact are rare. More often, students encounter a patchwork of course experiences as they move through a degree program's course requirements. Most of the

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research on the impact of transformations is limited to outcomes for students in a particular transformed course, while longitudinal studies (longer than one semester) are uncommon, despite the fact that this was one of the priorities noted in the now 10-year-old National Academies consensus report on discipline-based education research.[1] This lack of longitudinal research can perhaps be attributed to various causes, including the difficulty in conducting long-term studies, since students may disperse among many pathways and can be difficult to track and funding for such studies usually does not extend over extended time spans.[1] As a result, to our knowledge, there is little research on how students navigate among course type and course culture, either from the perspective of how students feel about such disconnects or from the standpoint of what students gain (or lose) in terms of learning as they transition from course to course.[28]

In this paper, we report how students fare as they move between a transformed organic chemistry course and a more traditional course and vice versa over a two-semester sequence. At our institution, these two types of organic courses are taught concurrently. Some sections are taught in a traditional manner, using a published textbook and instructional sequence,[29] while the transformed organic course uses the Organic Chemistry, Life, the Universe, and Everything (OCLUE) curriculum.[19] Students enroll in these courses often before instructors have been assigned and sign up for both courses in the two-semester sequence at the same time. This means that (1) they are not aware which curriculum they will be using and (2) they may unintentionally switch between curriculum types after the first semester. To minimize disruption, instructors agreed to cover the same material in the first semester so that students are prepared for the second semester. This arrangement results in an opportunity to compare student experiences, where students are free to choose their own schedules but may have different experiences depending on the sequence of courses they take. In this study, we examine how switching after the first semester impacts the ways in which students respond to two sets of tasks that we have studied previously.[30,31] Finally, we discuss the implications for students who are exposed to different expectations, instructional methods, and course cultures.

■ THEORETICAL FRAMING I: COURSE CULTURE

For any course, there is a set of norms that the instructors and students participate in as they collectively navigate the expectations and activities in the course. Such norms, which are often implicit rather than explicit, are sometimes referred to as the course culture, which may be thought of as "systems of meaning and practices that embody group norms."[32] Ways in which an instructor might communicate these "systems of meanings and practice" are not only the structure, content and expectations of the learning environments, and the types of assessments but also the ways in which students are expected to engage with the content of the course. For example, both traditional and transformed sections of OChem are taught in large lecture halls with 360 students with accompanying smaller recitations. However, the ways that two types of courses are enacted are different, resulting in our finding that different course cultures appear to result.[33,34]

In traditional sections, the class resources are a commercially published textbook[29] and recommended end-of-chapter homework problems, instruction is via lecture, and the course grade is comprised solely of student performance on several high-stakes tests and a final exam. While recommended homework problems are assigned, completion does not contribute to the course grade. Recitation sections are offered, in which graduate student assistants go over the homework or give short quizzes. In effect, as we have discussed in previous reports,[33,34] the traditional course does not explicitly support student engagement with the material, and the high-stakes tests may serve to focus students' attention on the types of questions on the test, rather than the course material itself.

The transformed sections use an open-education-resource textbook (Organic Chemistry, Life, the Universe and Everything, OCLUE)[19] and the homework system beSocratic;[35] a significant proportion of the course grade (40%) is allocated to activities where students are explicitly told that they will earn credit for "good faith effort" rather than correctness and that they should try to complete the tasks, even if they do not know the "correct" answer.[33,34,36] This approach to formative assessment tasks is intended to signal the value of the messiness in learning; it is the space where students are allowed to make mistakes and receive formative feedback. The OCLUE lecture sections are somewhat more interactive than traditional lectures, with clicker questions and short group activities interspersing the lectures. In recitation sessions, students work in groups to complete more complex tasks. However, perhaps the major difference between the two approaches is the expectations for what students should be able to do with their knowledge. Assessments in the traditional sections typically include completing reactions, drawing mechanisms, devising syntheses, and identifying substances from spectroscopic data; that is, the kinds of organic chemistry assessments found in many courses.[34] While OCLUE students are also expected to complete such tasks, they are also asked to construct explanations and reason about phenomena; in other words, they are often asked to explain how and why something happens and to provide explicit reasoning in both formative and summative assessments.[30]

Interestingly, it appears that students are aware of the differences in expectations between the two courses. When asked, "what are you assessed on" or "how are you expected to think", the majority of the OCLUE students indicated that they were assessed on ideas that were coded as "apply and reason", such as "reasons why things happen a certain way". In contrast, students from the traditional section were more likely to indicate that they believed they were assessed on memorization, for example "the majority of the exams are memorization of the reactions".[33] It is almost certain that this outcome was not the intent of the instructors of the traditional sections, but written responses of the students imply that they perceived that their role in the course was to memorize a great deal of information.

When the course operations and expectations are taken together with the student perceptions,[33,34,36] it appears that the traditional and OCLUE sections developed a different class culture, which we might expect to have impacts on the outcomes for each type of course.

■ THEORETICAL FRAMING II: RESOURCE ACTIVATION

In addition to experiencing a different course culture, students in traditional and OCLUE sections are expected to provide evidence of their knowledge in different ways. As noted earlier, students perceive that memorization is the major mode of assessment in the traditional course, while OCLUE students understand that they need to use their knowledge to reason with it. For example, while students in both courses are expected to be able to predict the outcome of an S_N2 reaction, in OCLUE,

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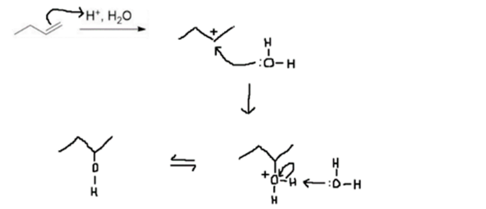
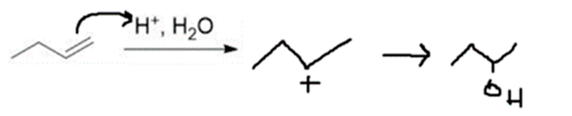
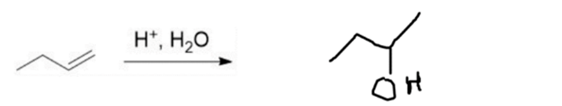
Code Grouping	Description of Code Grouping	Student Example
Plausible Product & Plausible Arrows	Student drew mechanistically reasonable steps and a plausible product	
Plausible Product & Mixture of Plausible and Incorrect Arrows	Student drew a mixture of mechanistically reasonable steps, incorrect arrows, and a plausible product	
Plausible Product & Incorrect or No Arrows	Student drew no arrows or incorrect arrows and a plausible product	
Incorrect Product & Mixture of Plausible and Incorrect or No Arrows	Student drew a mixture of mechanistically reasonable steps, incorrect arrows, and an incorrect product	

Figure 1. Overarching code groupings for all reactions. The color scheme shows the colors of the code groupings in the graphs in the Results section.

students are also asked to explain in words why the reaction proceeds as it does. This requires students to explicitly state and connect ideas about what makes a good nucleophile or leaving group and why the substrate is susceptible to nucleophilic attack. Certainly, traditional students are also taught these ideas, but the typical assessments do not require them to be explicitly stated.

In our previous work, we used the resources perspective on learning to understand this process. We know that students are not blank slates and that they "come to the classroom with preconceptions about how the world works".[4,37] This prior knowledge as well as the knowledge that students learn during instruction can be thought of as conceptual resources.[38] These resources act as the building blocks that must be activated, engaged with, and selected for productive use in order to "[help] students 'unravel' and 'reweave' the strands of their knowledge and understanding" within their discipline.[39] Using this perspective, the difference between expectations in OCLUE and traditional is best seen in the expectations for what students should know and be able to do for each course, which is reflected in the types of assessment items used in each course. In OCLUE, students are explicitly expected to connect their conceptual resources to explain and predict phenomena on both homework tasks and exams. Such activities are specifically designed to activate appropriate resources[38] and provide opportunities for students to connect them together, ideally resulting in a more expert-like knowledge structure in which their conceptual resources are connected, contextualized, and made useful.[37] While the traditional students may also be using these resources, the assessment tasks do not elicit evidence of this connection of the resources process. For example, a question in which students are asked to predict a product could be answered by memorization; whereas if they are asked to explain both how and why a particular product is formed, they must explicitly connect ideas about electrostatic interactions, bonding, stability, and reactivity. Consequently, students who participate in courses where these explicit connections are not required seem more likely to perceive each reaction or each idea as separate or not necessarily connected.[33]

■ BUILDING ON OUR PRIOR WORK

We have previously reported on specific outcomes for students who take either the full two-semester OCLUE sequence or the full two-semester traditional sequence,[30] and we use some of these data and coding schemes for the present study. Therefore, we briefly discuss two of these prior studies here: prior Study 1 shows how students draw mechanistic arrows for familiar and unfamiliar reactions,[31] and prior Study shows how students construct a causal mechanistic explanation about how and why a simple nucleophilic substitution reaction occurs.[30]

Prior Study 1: Mechanistic Arrow Use

In this study, we investigated how students draw mechanistic arrows to predict the products of both familiar and unfamiliar reactions.[31,40] We revised a coding scheme from a previous report[40] to compare how matched cohorts of students from OCLUE and traditional courses addressed each task. The full coding scheme may be found in the previous reports (Tables S4–S8).[31] We defined a plausible mechanism as one where mechanistic arrows start at a source of high electron density and end at a location of low electron density, while a plausible product may be either the expected major product or minor product that makes mechanistic sense for this reaction. Students were classified into four separate groups based on the following criteria: (1) a plausible product via a plausible mechanism, (2) a plausible product via a mixture of mechanistically reasonable steps and incorrect arrows, (3) a plausible product with incorrect arrows or no arrows, and (4) a chemically implausible product with either a mixture of mechanistically reasonable steps and incorrect arrows or no arrows. An example of a student response for each code is shown in Figure 1.

This coding scheme was used to characterize responses to six different prompts.[31,40] Here, we provide examples of student

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responses for the two reactions that are further explored in this paper: a familiar reaction (electrophilic addition of water to alkene) and what was, to our knowledge, an unfamiliar reaction (a ring closure at a carbonyl, as shown in Figure 2) for which students should have been able to predict a product by using mechanistic arrow pushing. Responses from students who had an OCLUE for both semesters of OChem (OCLUE−OCLUE) and those who had a traditional course for both semesters of OChem (traditional−traditional) were characterized. Our analysis showed that by the end of OChem 2, the majority of students (75%) from both cohorts were able to predict the product for the familiar reaction. However, there was a large difference between the numbers of students who used appropriate mechanistic arrows to reach the plausible product. 64% of students in the OCLUE−OCLUE cohort drew plausible arrows and a plausible product, while 21% of the traditional−traditional students drew plausible arrows and a plausible product.[31]

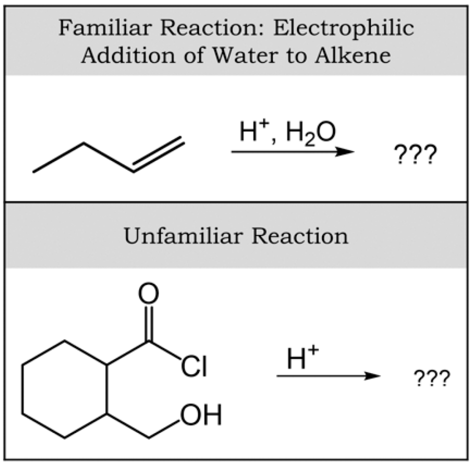

Figure 2. Summary of the familiar and unfamiliar reactions administered to participants.

When students were asked to draw a mechanism to predict the product for an unfamiliar reaction, the difference between the two cohorts became even more apparent. Forty-five percent of the OCLUE−OCLUE cohort drew a plausible product, with 42% using at least some appropriate mechanistic arrows, whereas 8% of traditional−traditional students drew a plausible product, with 4% drawing some appropriate mechanistic arrows.[31]

Prior Study 2: Causal Mechanistic Reasoning

While "arrow pushing" is the explicit manifestation of how a reaction mechanism occurs, the ability to draw a mechanism relies on a great deal of implicit knowledge about how and why arrows are drawn in such a particular way. In our work, we have explicitly linked the ability to draw mechanistic arrows with the scientific practice of constructing causal mechanistic explanations, in particular about how and why reactions occur.[30,41,42] We have built on prior work[30] to define causal mechanistic explanations (CM) as those that include reasoning both about how the electrons move during the reaction and about the electrostatic interactions that can cause this movement. The full coding scheme may be found in the previous reports (Table S1).[41] An example of a student response that was characterized as a causal mechanistic explanation for a simple S_N2 reaction on an alkyl halide was "the carbon has a partial positive on it due to the Br and so the negatively charged O attacks positive carbon with its lone pair breaking the bond of C−Br and those electrons go to the Br".[30] Such explanations provide both the what and the why of the electron movement during a reaction and may be considered as the verbal (written) accompaniment to what students should be thinking about as they draw mechanistic arrows. They also require students to explicitly connect and use conceptual resources, such as electrostatic attraction and bond polarity, to construct the explanation.

We have characterized a spectrum of responses that range from descriptive to causal to causal mechanistic. For simplicity in this paper, we have condensed this coding scheme into two categories: causal mechanistic (which includes discussions of both electron movement and electrostatic interactions) and noncausal mechanistic (everything else). The expanded coding characterizations are provided in Figure S10 and are published elsewhere.[30] We have reported longitudinal trends in student reasoning for a simple S_N2 reaction for two matched (by prior achievement and demographic information) cohorts: OCLUE−OCLUE and traditional−traditional.[30] In their first semester, both cohorts engaged in CM reasoning similarly, with 56−58% of both cohorts providing a CM response. However, by the end of OChem 2, the percent of OCLUE−OCLUE students who provided a CM response increased to 65%, whereas the percent of traditional−traditional students' responses decreased to 40%.[30] This trend was replicated the following year.[30]

RESEARCH QUESTION GUIDING THIS WORK

In the two prior studies, we showed that OCLUE students were more likely to draw mechanisms to predict products and more likely to provide causal mechanistic explanations for why such products are formed compared to traditional students at the end of OChem 2. The question here is, what happens to students who switch sections? Here, we report on students who switched course types to compare the outcomes to the previous findings for both drawing mechanistic arrows (Study 1) and causal mechanistic reasoning (Study 2). The study is guided by an overarching research question:

What is the impact of switching between a transformed organic chemistry course and a traditional organic chemistry course, as measured by:

a) students' use of mechanistic arrows to predict a product (Study 1)?
b) students' engagement in causal mechanistic reasoning (Study 2)?

METHODS

Student Participants

In this report, we present findings from 433 students divided into four cohorts based on their OChem course experience pathways. Students who were enrolled in OCLUE for two consecutive semesters will be referred to as OCLUE−OCLUE (n = 102), while students who were enrolled in a traditional OChem course for both semesters will be referred to as traditional−traditional (n = 125). These two-part names are meant to indicate the first and second semester course experiences for that group. As noted earlier, because of scheduling restraints and the fact that students enroll months before instructor assignments are listed, some students did not take the same organic course type for their first and second semester (i.e., they may take OCLUE for OChem 1 and then

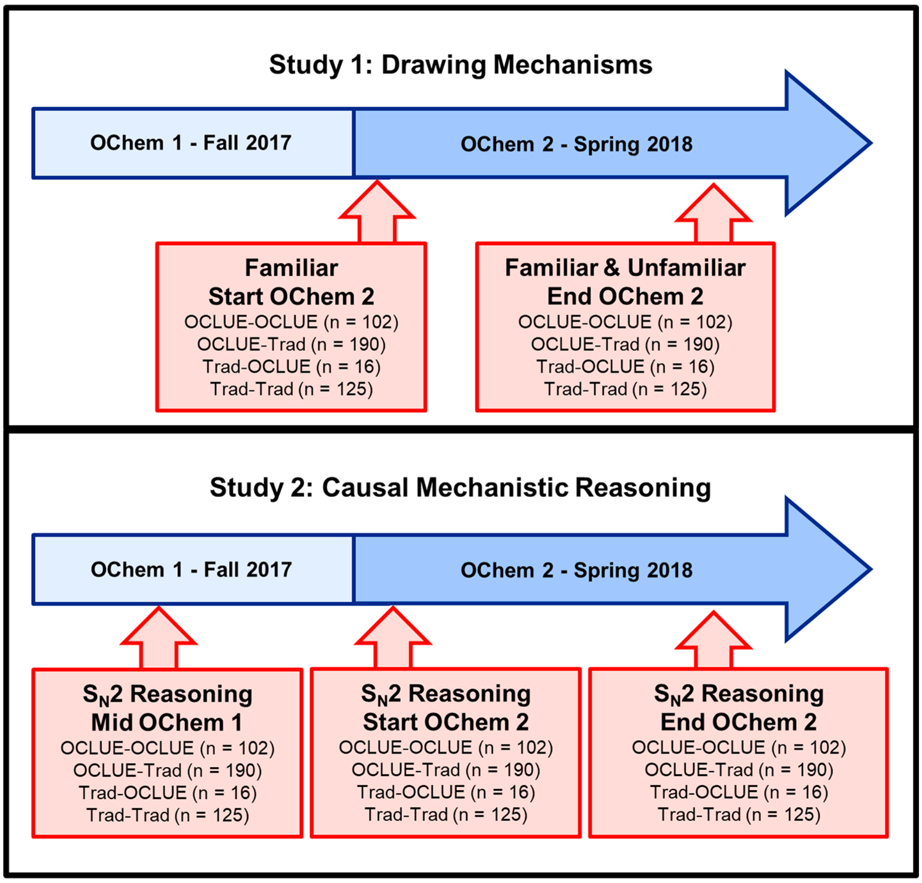

Figure 3. Summary of the data collection.

take traditional OChem 2, or vice versa). This led to an OCLUE−traditional cohort (n = 190) and a traditional−OCLUE cohort (n = 16). The OCLUE−traditional cohort is larger than the others because in the fall semester, there were two sections of the OCLUE course offered and only one section of the traditional course, while in the spring, there were two sections of the traditional course offered and only one section of the OCLUE course. This resulted in more students taking the OCLUE−traditional pathway. In the 2017−2018 academic year, there were two sections of OCLUE offered for OChem 1 and one section of traditional OChem 1. In the spring, there was one section of OCLUE offered and two sections of traditional offered for OChem 2. This means there were many more opportunities for students to be enrolled in the OCLUE−traditional course pathway, resulting in the larger cohort (n = 190), and fewer opportunities for students to be enrolled in the traditional−OCLUE pathway, resulting in a smaller cohort (n = 16). As a result, we do not report statistical analyses of data from the traditional−OCLUE cohort, but we include data from these few students to show the trends for descriptive purposes only. Figure 3 shows a summary of the administration of the prompts.

A strength of this combined study is that all 433 students responded to all the prompts at each of the time points discussed in the Data Collection section. We note that the student sample is slightly smaller than that of the previously published cohorts because we are limiting the analysis to students who took all of the prompts. We further refined the sample by including only those students for whom we could record complete general chemistry 1 and 2 course grades, organic chemistry 1 and 2 course grades, an ACT score, and their GPA prior to starting organic chemistry. Initially, there were 905 students enrolled in the OChem sequence, and after refining the cohorts based on the above criteria, 433 students remained for our study. Mann−Whitney U tests were used to compare each of these cohorts based on course grades, GPA prior to organic chemistry, and their ACT scores. Analyses were run in SPSS, and results are provided in Tables S1 and S2. No differences were found when comparing general chemistry grades, GPA prior to starting organic chemistry, and organic chemistry 1 grades; however, a few small differences were observed in organic chemistry 2 grades and ACT scores. Students enrolled in the traditional course for OChem 2 had higher OChem 2 grades when compared to OCLUE students (small effect size).[43] OCLUE−traditional students had higher ACT scores compared to traditional−traditional students (small effect size).[43] There is no apparent grade penalty for students who switch sections.

Data Collection

Both the mechanistic arrow tasks (Study) and the causal mechanistic reasoning tasks (Study) were administered using the beSocratic system,[35] an online formative assessment tool that allows students to write and draw responses. All data is recorded and can be replayed and coded later. For OCLUE students, these activities were part of their homework assignments. As noted, OCLUE homework assignments are not graded for accuracy and count for 15% of their course grade. These tasks were given as extra credit, and counted for <1% of their total course grade. For traditional students, the assignments were also offered as extra credit (approximately 2% of their course grade). In the following subsection, we describe each of the tasks in full detail. Because of scheduling logistics, at

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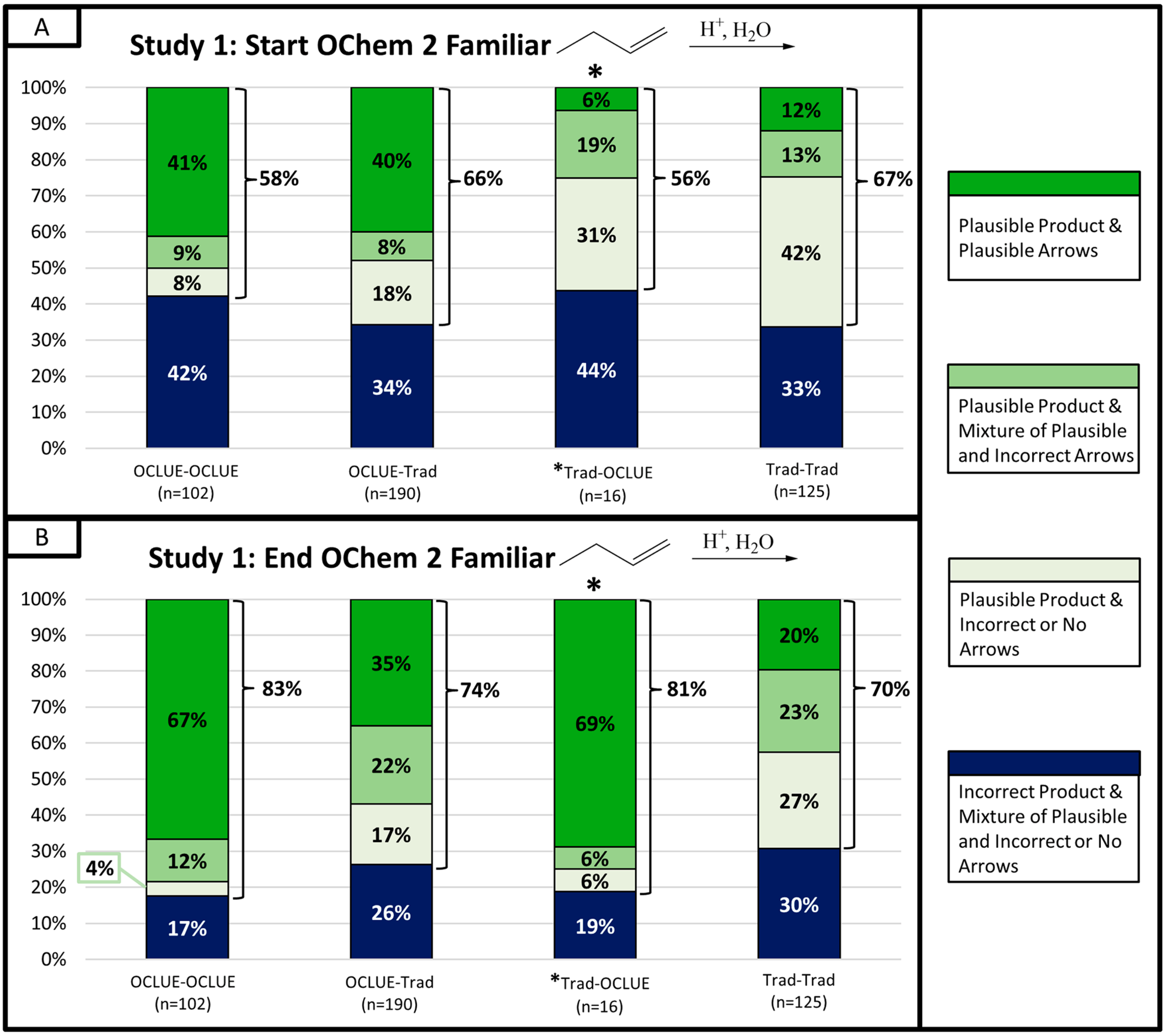

Figure 4. Percent of arrow use and product drawn for a familiar reaction for each cohort. The traditional−OCLUE cohort is small ($n = 16$) and marked with an asterisk.

the beginning of the second semester time point, the activities were administered to OCLUE students in the first week of the semester and to traditional students in the second week.

Study 1: Mechanistic Arrow Use Data Analysis

The task asked students to "predict the product of the following reaction by drawing a mechanism." Students were provided with structures of the starting materials and reagents and a space to draw mechanistic arrows, intermediates, and products. Although students completed several tasks, here we report only two: (1) a familiar task involving the acid-catalyzed hydration of an alkene and (2) a more complex task involving an intramolecular reaction that, to our knowledge, they had not seen before. These prompts were chosen to explore students' responses to a familiar and unfamiliar reaction, though there were other familiar prompts administered that could be investigated in future studies. However, to explore a more manageable set of data, only one familiar response was initially investigated. Screenshots of the familiar and unfamiliar task are provided in Figures S3 and S4 and published elsewhere.[31] By timing the data collections at the start and end of OChem 2, our intent was to capture both what the students learned in OChem 1 (at the start of OChem 2) and the impact of their OChem 2 course at the end of the semester. Responses from both time points were coded anonymously by author S.K.H. and a trained postbaccalaureate coder such that the coders were not aware of the students' backgrounds when reviewing a response. Both coders evaluated 60 random responses from each prompt to obtain Cohen's kappa values, which ranged from 0.78−1.0, indicating substantial agreement. The full coding scheme and kappa values may be found in the previous reports and in Tables S9 and S13.[31,43]

Study 2: Causal Mechanistic Reasoning Data Analysis

This task presented students with Lewis structures for the reactants and products for a simple S_N2 reaction followed by the following prompts: (i) *How would you classify this reaction?* (ii) *Please describe the sequence of events that occur at the molecular*

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Table 1. Differences in Students' Use of Arrows for a Familiar Reaction between Course Type[a]

time point	cohorts	χ^2 (df = 1)	*p*-value	Cramer's *V*
Start OChem 2	OCLUE−OCLUE traditional−traditional	25.426	<0.001*	0.335 (medium)
Start OChem 2	OCLUE−OCLUE OCLUE−traditional	0.038	0.845	0.011
Start OChem 2	traditional−traditional OCLUE−traditional	28.774	<0.001*	0.302 (medium)
End OChem 2	OCLUE−OCLUE traditional−traditional	51.769	<0.001*	0.475 (medium to large)
End OChem 2	OCLUE−OCLUE OCLUE−traditional	26.331	<0.001*	0.300 (medium)
End OChem 2	traditional−traditional OCLUE−traditional	8.968	0.003*	0.168 (small)

[a]Significant values are indicated with an asterisk (*). For all Chi-square analyses, a Sidak adjusted α of $\alpha = 0.017$ was used.[44] Cramer's V is used to interpret the magnitude of a significant finding; it is interpreted as a small effect size of between 0.1−0.3, a medium effect size of between 0.3−0.5, and a large effect size of greater than 0.5.[43]

level during the reaction shown above. (iii) *Please explain why these reactants interact.* (iv) *For the following reaction, please draw arrows in the blue box to indicate how this reaction occurs.* (v) *Now please explain why you drew your arrows as indicated.* In this publication, we only report on students' reasoning, since their mechanistic arrow drawings for this prompt have been reported elsewhere.[30] A screenshot of this prompt is provided in Figure S9 and has been published elsewhere.[30] We should note that this prompt is designed to elicit only the mechanism of the reaction as it proceeds. If we wanted to elicit other aspects (such as the direction of the reaction or the rate of the reaction), we would have to design a different prompt that would help students consider, for example, leaving group ability, activation energy, and/or nucleophile strength.

This prompt was administered to students in both the OCLUE and traditional courses three times during the two semesters. The first data collection took place right after students learned about S_N2 reactions in the middle of their OChem 1 course, once again at the start of OChem 2, and finally at the end of OChem 2.

The written explanations were exported out of the beSocratic platform[35] into a spreadsheet, and all four pieces of the explanation (i.e., "classify...", "describe what...", "explain why...", and "explain your arrows...") were coded together and characterized according to the previously published scheme. As discussed above, for simplicity, we will only report responses in terms of causal mechanistic or noncausal mechanistic here, but the full characterization results are reported in Figure S11. All explanations were coded by author O.M.C. with the assistance of two undergraduate coders. In instances where disagreements arose, coding was discussed until a complete agreement was reached.

Reducing Potential Bias

We recognize the biases that are inherent when researchers investigate the curricular impacts of an intervention that they themselves designed. In an effort to reduce the impact of these biases, responses were collected and analyzed in such a way that they were de-identified from their course type and coded anonymously. This was done so that coders were not aware of students' course type or identity while coding the responses.

RESULTS

Study 1: Mechanistic Arrow Use

As discussed earlier, our original work found that similar percentages of OCLUE−OCLUE and traditional−traditional students produce a plausible product for a familiar reaction.[31] However, we observed that students enrolled in the OCLUE−OCLUE sequence were significantly more likely to draw all mechanistic steps correctly (Plausible Product and Plausible Arrows) than those in the traditional−traditional course sequence (with a Sidak adjusted α level[44] of 0.017 per test ($\alpha = 1 - (1 - 0.05)^{(1/3)}$) and a medium effect size of Cramer's V = 0. 335). To avoid the likelihood of making any type 1 errors in determining significance with multiple Chi-square tests, we used the more conservative Sidak adjusted α value of 0.017 instead of the usual 0.05.[44] Cramer's V is used to interpret the magnitude of a significant finding, and it is interpreted as small effect size between 0.1−0.3, a medium effect size between 0.3−0.5, and a large effect size greater than 0.5. As noted earlier, we have excluded the traditional−OCLUE cohort from any statistical analyses because their number is too small ($n = 16$).

The data from our analyses of all four cohorts (Figure 4 and Table 1) show an interesting pattern. At the start of the second semester, students' responses appear to reflect their previous experiences in OChem 1. That is, students who have switched from the OCLUE to the traditional method have performances similar to their OCLUE peers, while the performances of the students who switched from the traditional method to OCLUE look like those of their traditional-only peers. However, by the end of the second semester, we see that the situation has changed. While all cohorts are still able to draw the product for acid-catalyzed hydration, the percentage of students in the OCLUE−traditional cohort who draw mechanisms has decreased significantly as compared to the OCLUE−OCLUE cohort. That is, a smaller percent of students who transferred from OCLUE to traditional use curved arrows to predict the product than those who remained in OCLUE. Conversely, there is a greater percentage of students who switched from traditional to OCLUE who draw mechanistic arrows than those who stay in the traditional curriculum for both semesters.

By the end of study 1, the patterns of mechanism use for the students who switch tend to resemble the main cohort into which they switched. As shown in Table 1, while the performances of the OCLUE−OCLUE and OCLUE−tradi-

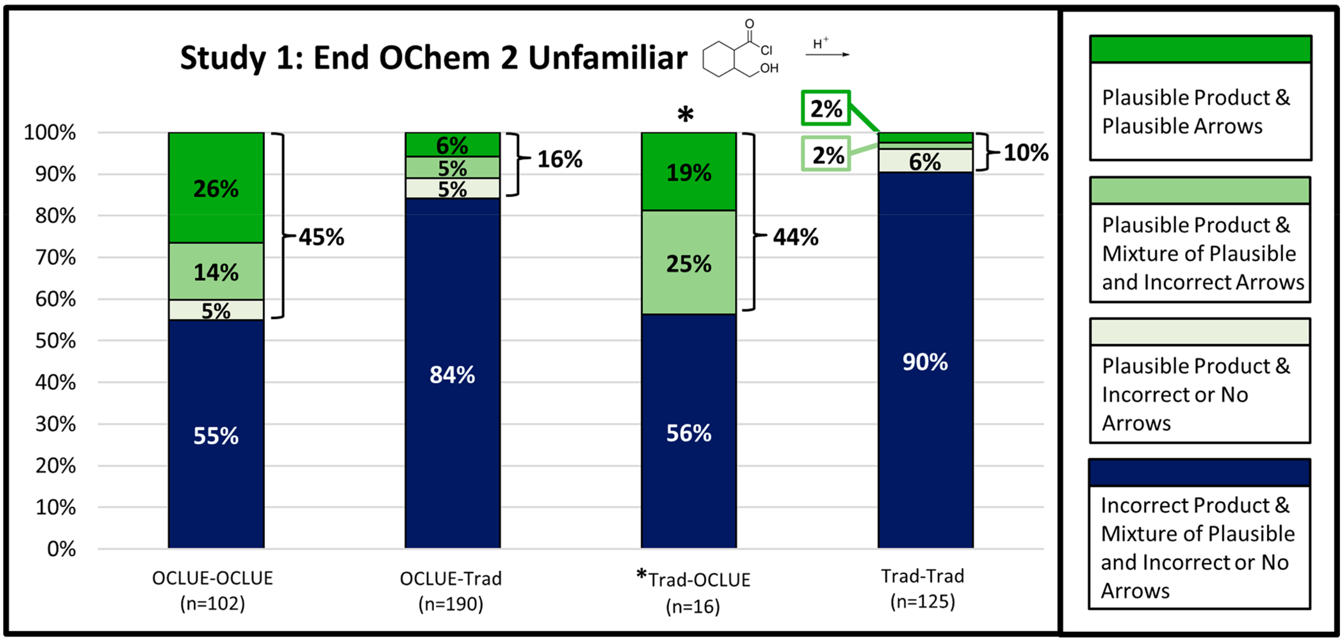

Figure 5. Percent of arrow use and products drawn for an unfamiliar reaction for each cohort. The traditional−OCLUE cohort is small ($n = 16$) and marked with an asterisk.

Table 2. Differences in Students' Use of Arrows for an Unfamiliar Reaction between Course Type[a]

time point	cohorts	χ^2 (df = 1)	*p*-value	Cramer's *V*
End OChem 2	OCLUE−OCLUE traditional−traditional	28.374	<0.001*	0.354 (medium to large)
End OChem 2	OCLUE−OCLUE OCLUE−traditional	25.077	<0.001*	0.293 (medium)
End OChem 2	traditional−traditional OCLUE−traditional	2.040	0.080	0.153 (small to medium)

[a]Significant values are indicated with an asterisk (*). For all Chi-square analyses, a Sidak adjusted α of $\alpha = 0.017$ was used.[44] Cramer's *V* is used to interpret the magnitude of a significant finding; it is interpreted as a small effect size of between 0.1−0.3, a medium effect size of between 0.3−0.5, and a large effect size of greater than 0.5.[43]

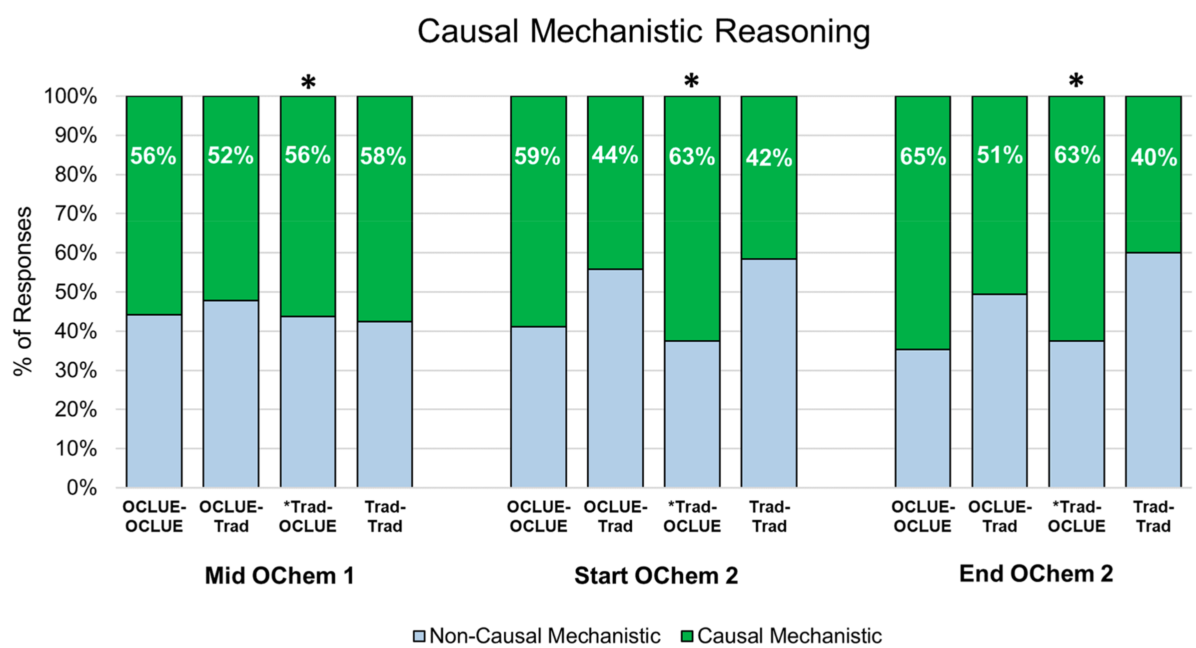

Figure 6. Percent of causal mechanistic responses for each cohort across the three time points. The traditional−OCLUE cohort is small ($n = 16$) and marked with an asterisk.

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Table 3. Chi-Square Tests to Determine Any Association between Cohort Membership and Causal Mechanistic Reasoning Characterization[a]

time point	cohorts	χ^2 (df = 1)	p-value	Cramer's V
Mid OChem 1	OCLUE−OCLUE traditional−traditional	0.068	0.795	0.017
Mid OChem 1	OCLUE−OCLUE OCLUE−traditional	0.381	0.537	0.036
Mid OChem 1	traditional−traditional OCLUE−traditional	0.917	0.338	0.054
Start OChem 2	OCLUE−OCLUE traditional−traditional	6.666	0.010*	0.171 (small to medium)
Start OChem 2	OCLUE−OCLUE OCLUE−traditional	5.670	0.017	0.139 (small to medium)
Start OChem 2	traditional−traditional OCLUE−traditional	0.209	0.647	0.026
End OChem 2	OCLUE−OCLUE traditional−traditional	13.720	<0.001*	0.246 (small to medium)
End OChem 2	OCLUE−OCLUE OCLUE−traditional	5.403	0.020	0.136 (small to medium)
End OChem 2	traditional−traditional OCLUE−traditional	3.360	0.067	0.103 (small)

[a]Significant values are indicated with an asterisk (*). For all Chi-square analyses, a Sidak adjusted α of α = 0.017 was used.[44] Cramer's V is used to interpret the magnitude of a significant finding; it is interpreted as a small effect size of between 0.1−0.3, a medium effect size of between 0.3−0.5, and a large effect size of greater than 0.5.[43]

tional cohorts are similar at the beginning of OChem 2, by the end there is a significant difference with a large effect size[43] between the two cohorts. Similarly, at the beginning of OChem 2, the performances of the OCLUE−traditional and traditional−traditional cohorts are significantly different with a large effect size, and while they are still statistically different at the end of OChem 2, the effect size is now small.[43]

For the second part of study 1, students were asked to use mechanistic arrows to predict a plausible product for a reaction that, to our knowledge, students had not seen before. That being said, students should be able to use the principles of mechanistic arrow pushing and an understanding of how carbonyl functional groups behave to predict plausible products for this reaction. In the original study using this prompt,[40] students struggled to complete this task, with only about 8% of the students successfully drawing a plausible product.[40]

For this study, students were asked to complete this task at the end of OChem 2, and the responses were coded in a similar fashion to the familiar reactions. While students find this task much more difficult, it is now clear that the use of arrow pushing does help students produce a plausible product. We see that 45% of the students of OCLUE−OCLUE and 44% of the students of traditional−OCLUE drew a plausible product, the majority of whom drew at least some plausible mechanistic arrows. However, only 16% of OCLUE−traditional and 10% of traditional−traditional students proposed a plausible product, as shown in Figure 5 and Table 2.

Again, the same pattern emerges, in which the switchers' responses are closer to the responses typical of the course in which they are enrolled.

Study 2: Causal Mechanistic Reasoning

As noted earlier, in this task, students were asked to explain in words how and why a simple S_N2 reaction proceeds. The task was administered to students at three time points: midway through the first semester (mid OChem 1) and at the beginning and end of OChem 2. At the mid OChem 1 time point, students had learned about S_N2 reactions in both the OCLUE and traditional courses. As shown in Figure 6, students in both the OCLUE and traditional courses provided similar types of responses, with 52% and 58%, respectively, giving a causal mechanistic explanation. This finding indicates that students in both courses interpret the prompt in similar ways and are equally capable of engaging in causal mechanistic reasoning. We found no statistically significant association at this time point, as shown in Table 3, which shows a series of 2 × 2 Chi-square tests each time point, to determine if there was any association between cohort membership (OCLUE−OCLUE, OCLUE−traditional, or traditional−traditional) and students' reasoning (CM or non-CM).

However, at the start of OChem 2, we see that both the traditional−traditional students and the OCLUE−traditional students appear to have lost ground. Upon moving into the traditional course, we see that the percentage of OCLUE−traditional students who construct causal mechanistic explanations drops from 52% to 44% after just a week or two of instruction. Similarly, traditional−traditional students drop from 58% to 42% causal mechanistic, and while this change is significant, the effect size is small to medium (χ^2 = 6.666, p = 0.010, Cramer's V = 0.171, small to medium effect size).[43]

At the third administration of the prompt at the end of organic chemistry 2 (end OChem 2), there is little change from the start OChem 2 percentages. Overall, the same trend as study 1 is apparent, although it seems to emerge earlier, and the effect is somewhat smaller: the students who switched courses tend to reason similarly to the students who were consistently enrolled in the course type into which they enrolled.

■ DISCUSSION

The goal of this study is to better understand what happens as students move between different courses that ostensibly cover the same material but may use different teaching methods and have different classroom cultures. In this study, we find students who switch sections after one semester of a two-semester course tend to perform similarly to the course into which they switch.

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Most problematically, fewer students are likely to use mechanistic arrows or to provide a mechanistic explanation if they switch from a transformed to a traditional course section.

One might hope that once students have learned a particular skill, or what Krist et al. call an epistemic heuristic (a general thinking strategy), students would subsequently use that skill to guide their reasoning about phenomena.[45] We might expect that once learned, the ability to correctly draw mechanistic arrows or to construct causal mechanistic explanations would persist through the next course in the sequence. Surprisingly, we find that switching from the OCLUE program to the traditional method after the first semester results in what appears to be a loss of acquired skills for many students. On the other hand, while the numbers of students are smaller, it appears that some students can acquire these ways of thinking upon transferring into a course with a different emphasis. It is worth pointing out that there appears to be no overall grade penalty for switching (Table S1), despite the fact that each course tends to emphasize and value different aspects of organic chemistry.

These findings suggest that students can and do adapt quickly to course culture and assessment strategies; explicit and more subtle implicit messages about what is important in the course are quickly learned and acted upon. However, this positive finding is offset by our data showing that some students who transfer from the transformed courses do not retain, or at least no longer use, what they learned. There are several possible reasons for this. The expectations and course culture in the two different iterations of organic chemistry are manifestly different,[33,34,36] and different types of thinking and problem solving are valued and rewarded in each course. In OCLUE, students routinely (at least twice a week) complete formative tasks for homework on beSocratic, which require them to engage in mechanistic reasoning at the same time as drawing electron pushing mechanisms. Whereas in the traditional course, students are certainly asked to draw mechanisms, but this is not coupled with such reasoning tasks. This is also apparent in traditional students' reported perceptions of the course; very few of these students believe that they are expected to apply reason in their organic course, while a majority of them believe they are expected to memorize the material.[33]

It is interesting, however, that the rate at which students change appears to be task-dependent. If we compare the beginning of OChem 2 performances for the switchers across studies 1 and 2, we see that for study 2, the switchers already behave more like the course into which they switched, whereas for study 1, these same students' performances still reflect the course from which they switched.[31] These data were recorded 1−2 weeks after the second semester began, and the study 2 results appear to indicate that the cultural norms of the class are quickly assimilated by students. Perhaps it has become apparent to students that explanations are not an integral component of the traditional course, and some students stop writing such detailed explanations. In contrast, these same students do persist in drawing mechanisms similar to their OCLUE−OCLUE peers 2 weeks into the course. This may be because mechanisms are emphasized in both courses, where instructors typically draw them with great frequency. However, by the end of the traditional course, many of the original OCLUE students have relinquished the use of mechanisms, so that they appear more like traditional−traditional students. This change becomes even more apparent in the results from the unfamiliar task (Figure 5), where the OCLUE−traditional cohort appears to find the task just as difficult as the traditional−traditional cohort. This task cannot be accomplished by memorization or pattern recognition; students who do not routinely use the tools of mechanistic reasoning and curved arrow mechanism drawing are unlikely to draw an appropriate product.

■ IMPLICATIONS

Transformed courses have been shown to improve important student outcomes, ranging from skills such as drawing Lewis structures[46] and mechanistic arrows[31,40,47] to more complex outcomes such as constructing explanations, models, and arguments and engaging in mechanistic reasoning.[30,41,42] The finding from this study that, for whatever reasons, some students tend to not retain, or at least use, their abilities if they transfer to a more traditional course means that the use of the "one shot" or "lone instructor" approach to transformation may make it difficult to achieve sustainable change. If we agree that course transformations such as the OCLUE curriculum can promote improvements in students' learning of ideas and practices that we value, then we must search for better ways to sustain and extend such transformations.

While we have provided evidence that even one course allows students to build useful knowledge, we also have evidence that these increases are fragile and easily lost. Because of the paucity of longitudinal studies, we do not know what "dose" of transformation would lead to lasting improvements in student learning. However, in a previous study, we did find that students who had taken a two-semester transformed general chemistry course (CLUE)[16] provided more sophisticated explanations for simple acid−base reactions at several points throughout a traditional two-semester organic course than students who had taken more traditional general chemistry courses.[41] That is, a two-semester general chemistry course that emphasized mechanistic reasoning appeared to have some lasting effect. That being said, we believe that it is in students' best interests that they see a coherent, sequenced approach to their science courses, in which scientific practices such as constructing models, explanations, and arguments are used to help students connect and use their resources and construct more expert-like knowledge structures.

It is our contention that there is a strong and positive link between constructing mechanistic explanations and drawing mechanisms. In our work where we analyze student mechanistic drawings, we see that students who are also expected to engage in constructing mechanistic explanations make more use of mechanistic arrows and are better able to use them to predict the products of unfamiliar reactions.[31] Indeed, we see this phenomenon in study 1, where students at the end of the OCLUE tend to use more mechanistic arrows and are far more successful in predicting the outcome of an unfamiliar reaction. In effect, they can transfer their skills to a new situation, which surely is an important goal, perhaps even the major goal, of education.

We propose that constructing mechanistic explanations can be an approach that helps students make connections among appropriate cognitive resources. An emphasis on reasoning throughout a course coupled with opportunities to practice on ungraded, formative (low-stakes) assessments makes these resources accessible, strengthens the connections between them, and leads to a culture that encourages a willingness to "try out" ideas without penalty. We also recognize that students are rational actors, and in a class where students perceive that memorization is an appropriate strategy for learning material,[33] then the ideas learned earlier (about how and why reactions

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occur) may seem less valuable and are not used. Whatever the reasons, our findings here have significant ramifications for the development of sustainably transformed sequences of courses.

LIMITATIONS

The limitations of this study are that it was conducted in a single university, and although there are quite large numbers of students in each cohort, it is not replicated (because of limitations due to scheduling and the COVID pandemic). The metrics used to compare the two student groups (shown in Tables S1 and S2) give us some insight into the demographic similarities between the two groups; however, using metrics such as course grade may not be all that informative for two instructors with different syllabi and different approaches to learning and assessment. Furthermore, while it is possible students might have self-selected into the course based on the instructor, students do enroll in the course before the instructor is listed and there is limited movement between sections once the semester starts. The two cohorts took all the assignments as extra credit activities on the beSocratic platform, which was used routinely for OCLUE but not for traditional sections. However, most traditional students took general chemistry using the same platform and therefore were familiar with it. Students in the traditional sections received more overall credit for completing the task with "good faith effort" than did those in OCLUE.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00345.

Additional information regarding students' demographic data, expanded coding schemes, and student responses over time (PDF)

Additional information regarding students' demographic data, expanded coding schemes, and student responses over time (DOCX)

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