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Complete List of Authors:	Watts, Field; University of Michigan, Department of Chemistry Gupta, Trisha; University of Michigan, Department of Chemistry Schmidt-McCormack, Jennifer; St. Ambrose University, Chemistry; Zaimi, Ina; University of Michigan, Department of Chemistry Gere, Anne; University of Michigan, Sweetland Center for Writing Shultz, Ginger; University of Michigan, Department of Chemistry

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Trisha Gupte,†[a] Field M. Watts,†[a] Jennifer A. Schmidt-McCormack,[b] Ina Zaimi,[a] Anne Ruggles Gere,[c] and Ginger V. Shultz *[a]

Teaching organic chemistry requires supporting learning strategies that meaningfully engage students with the challenging concepts and advanced problem-solving skills needed to be successful. Such meaningful learning experiences should encourage students to actively choose to incorporate new concepts into their existing knowledge frameworks by appealing to the cognitive, affective, and psychomotor domains of learning. This study provides a qualitative analysis of students' meaningful learning experiences after completing three Writing-to-Learn (WTL) assignments in an organic chemistry laboratory course. The assignments were designed to appeal to the three domains necessary for a meaningful learning experience, and this research seeks to understand if and how the WTL assignments promoted students' meaningful learning. The primary data collected were the students' responses to open-ended feedback surveys conducted after each assignment. These responses were qualitatively analyzed to identify themes across students' experiences about their meaningful learning. The feedback survey analysis was triangulated with interviews conducted after each assignment. The results identify how the assignments connected to students' existing knowledge from other courses and indicate that assignment components such as authentic contexts, clear expectations, and peer review supported students' meaningful learning experiences. These results inform how assignment design can influence students' learning experiences and suggest implications for how to support students' meaningful learning of organic chemistry through writing.

Introduction

Teaching and learning in organic chemistry are challenging because the discipline is highly conceptual and requires advanced problem-solving and critical thinking skills. These challenges are compounded by the need for students to develop specific learning strategies that may not directly transfer from general to organic chemistry (Anderson and Bodner, 2008; Grove and Bretz, 2012; Graulich, 2015). Because it is a challenging course even for students who are successful in general chemistry, organic chemistry classrooms can be high-stress environments with high rates of attrition (Karty et al., 2007; Anderson and Bodner, 2008; Grove et al., 2008; Hein, 2012). In response, chemistry education researchers are invested in understanding and measuring students' meaningful learning experiences in organic chemistry (Galloway and Bretz, 2015a, 2015b, 2015c; Galloway et al., 2016). Theories of meaningful learning address the challenges with learning organic chemistry by recognizing the interplay between affective, cognitive, and psychomotor components of learning. Meaningful learning theories posit that all three of these areas must be addressed for meaningful learning to occur (Novak, 1993, 2002; Bretz, 2001). To further support students' learning in organic chemistry, it is necessary to develop and research specific pedagogical approaches to support students' meaningful learning.

Meaningful learning in organic chemistry

Studies of meaningful learning in organic chemistry have theoretical grounding in Ausubel's (1963) theory of meaningful learning and Novak's (1993, 2002) theory of human constructivism. These frameworks both draw on the constructivist definition of learning as connecting new knowledge to prior knowledge. Ausubel (1963) posits three requirements for meaningful learning: (1) students' relevant prior knowledge, (2) instructors' organization of concepts to relate new information to students' prior knowledge, and (3) students actively choosing to incorporate new knowledge into their existing conceptual frameworks. Of these three requirements, only the second is within the instructors' control. Hence, it is necessary that instructors' curricular choices support students in relating new concepts to their prior knowledge. However, instructors can indirectly influence the third of these requirements by developing curricular materials that build sufficient interest in new concepts, encouraging students to actively make connections to their prior knowledge. Ausubel's theory of meaningful learning is related to Novak's

a. *Department of Chemistry, University of Michigan, Ann Arbor, Michigan 48109, United States.*
b. *Chemistry Department, St. Ambrose University, Davenport, Iowa 52803, United States.*
c. *Sweetland Center for Writing, University of Michigan, Ann Arbor, Michigan 48109, United States.*
† T. G. and F. M. W. contributed equally to this work
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(1993, 2002) theory of human constructivism, which encompasses three domains related to learning: the cognitive, affective, and psychomotor domains. The cognitive domain includes engaging conceptual knowledge and reasoning skills, the affective domain relates to attitudes and motivation towards learning, and the psychomotor domain involves motor skills and physical movement. Each of these domains is required for meaningful learning; that is, a learning experience must attend to all three domains for it to be meaningful.

Research on meaningful learning in the organic chemistry curriculum focuses on both faculty and student perspectives. Bretz *et al.* (2013) interviewed chemistry faculty about their goals for teaching undergraduate lab courses across general, organic, and upper-division laboratory courses. They analysed faculty responses through the lens of meaningful learning frameworks and found that faculty held goals pertaining to all three domains of meaningful learning. However, their analysis suggested that faculty teaching organic chemistry exhibited a marked decrease in their discussion of affective goals, instead emphasizing critical thinking and laboratory techniques. The affective goals that instructors did have included emphasizing the relevance of the content and skills taught in the laboratory to students' aspirations. This study suggests that organic chemistry instructors need to incorporate learning activities that specifically support the affective domain, because many laboratory courses already focus on the cognitive and psychomotor domains.

Meaningful learning has also been characterized from the students' perspective. Galloway and Bretz (2015a) developed the Meaningful Learning in the Laboratory Instrument (MLLI), which measures students' meaningful learning experiences in laboratory courses across the cognitive and affective domains. Administrations of the MLLI to students across general and organic chemistry suggest that students tend to have a variety of cognitive and affective expectations and experiences in chemistry laboratories (Galloway and Bretz, 2015b, 2015c). Galloway and Bretz' (2015b) national, cross-sectional study indicated that students with low affective expectations tended to have experiences that fulfilled their negative expectations. Further, their longitudinal study indicated that students' experiences can fail to meet their positive expectations. However, students' expectations tended to reset when beginning organic chemistry lab courses, even when expectations for general chemistry labs were not met (Galloway and Bretz, 2015c). That students' expectations are reset before organic chemistry provides opportunities to re-engage students with the affective domain of meaningful learning in this course. As each of these studies indicates, pedagogy in organic chemistry would benefit from attention to the affective dimension of meaningful learning.

Research qualitatively exploring chemistry students' affective experiences as they relate to laboratory learning experiences is limited (Flaherty, 2020). A study by Galloway *et al.* (2016) focused on the interplay between students' affective, cognitive, and psychomotor experiences by interviewing students in both general and organic chemistry laboratories. They found that the affective domain is closely linked to the cognitive and psychomotor domains and that students' affective experiences are linked to their approach to learning. In particular, their analysis suggested that students' differing sense of autonomy in the laboratory influenced a wide range of approaches to learning, from rote to meaningful strategies. Their findings indicate the need for further qualitative research exploring students' affective experiences. Furthermore, their results indicate a need for the design of learning experiences which help students develop a sense of autonomy and specifically support students' positive affective experiences. This finding is particularly important when considering the recent attention on developing hybrid and online laboratory courses (Enneking *et al.*, 2019; Hensen *et al.*, 2020). Research has suggested that general chemistry students completing virtual laboratory experiences develop similar cognitive and psychomotor skills as students completing in-person laboratories but report lower affective experiences (Enneking *et al.*, 2019; Hensen *et al.*, 2020). These studies, in particular, identify the importance for both hybrid and online laboratories to emphasize the value of laboratory learning experiences to students' lives and their career aspirations. Hensen *et al.* (2020) specifically call for learning interventions that can allow students to have positive affectual laboratory experiences.

Writing-to-Learn and meaningful learning

The existing research on students' meaningful learning experiences in organic chemistry laboratories suggests the need to explore pedagogical approaches that can support students' positive affective experiences. Such affective experiences relate to students' interest and motivation. These constructs are often aligned with relevancy, which, in turn, is influenced by instructors' curricular choices (Stuckey *et al.*, 2013). Prior research within chemistry indicated that lesson plans which appeal to topics relevant to students' lives can improve motivation for learning (Stuckey and Eilks, 2014). Studies of motivation for learning more generally have provided evidence for various influences that teachers' pedagogical choices can have on students' motivation (Schunk, 1991; Vansteenkiste *et al.*, 2006, 2009). Specifically, setting challenging goals for students, explaining the rationale for assignments, supporting learning from peer models, and providing timely feedback have been shown to support students' motivation (Schunk, 1991; Vansteenkiste *et al.*, 2006). In addition, students can have higher-quality motivation for when they perceive a teaching environment as providing clear structure and supporting their autonomy (Vansteenkiste *et al.*, 2009).

Prior research within chemistry education has investigated appealing to students' interest and motivation by developing curricula that incorporate authentic contexts (Gilbert, 2006; Pilot and Bulte, 2006). A component of these efforts requires the design of specific course materials that are relevant to students, which is important for encouraging students to make connections between new concepts and existing knowledge structures (Grove and Bretz, 2012). Therefore, it is necessary to research assignments within the organic chemistry context that are specifically designed to appeal to the affective domain of meaningful learning by supporting students' interests.

Writing-to-Learn (WTL) activities are instructional interventions that can complement the psychomotor domain emphasized in the laboratory by specifically appealing to the cognitive and affective learning domains. They are designed to engage students with material while supporting their conceptual understanding through the process of writing, with a focus on improving content knowledge rather than improving writing ability (Rivard, 1994; Reynolds *et al.*, 2012; Klein and Boscolo, 2015). Research on WTL assignments has been conducted in chemistry (Shultz and Gere, 2015; Moon *et al.*, 2018, 2019; Finkenstaedt-Quinn *et al.*, 2019, 2020; Schmidt-McCormack *et al.*, 2019; Watts *et al.*, 2020; Zaimi *et al*., 2020), biology (Halim *et al.*, 2018), and engineering courses (Finkenstaedt-Quinn *et al.*, 2017), demonstrating how WTL assignments with peer review and revision serve to elicit students' content knowledge while supporting students' understanding of targeted concepts.

While WTL assignments have been demonstrated to support students' conceptual learning, research is necessary to investigate the components of WTL assignments that engage students in meaningful learning. Previous literature has identified that WTL prompt design is important for supporting students' conceptual learning (Anderson *et al.*, 2015; Gere *et al.*, 2019). Notably, one of the essential components is "meaning-making," defined as the requirement that WTL assignments have students apply their existing knowledge to new situations. Other important features are that WTL assignments have rhetorical components to highlight the relevance of content to authentic situations—such as a specified genre, role, and audience—and that WTL assignments include interactive components such as peer review (Anderson *et al.*, 2015; Gere *et al.*, 2019). While these studies have illustrated assignment components that support students' conceptual learning, it is valuable to also understand students' meaningful learning experiences with WTL assignments. This understanding is necessary, because students—rather than instructors—are responsible for making the decisions to integrate new ideas into their existing knowledge structures.

Research on undergraduate students' meaningful writing experiences has found that assignments that engage students with both content and peers while connecting to students' current and future identities are more meaningful for students (Eodice *et al.*, 2016). To build upon these findings, it is necessary to specifically research students' meaningful learning experiences with WTL assignments in STEM courses. Furthermore, prior studies of WTL interventions in STEM courses have focused on evaluating the implementation of a single assignment rather than examining the outcomes of implementing a series of WTL assignments within a course. Analysing a series of WTL assignments is valuable, especially for understanding similarities and differences between individual assignments and how, when implemented throughout a course, they might support students' meaningful learning experiences over a semester.

Research questions

This research presents the qualitative analysis of second-semester organic chemistry laboratory students' meaningful learning experiences with a set of Writing-to-Learn assignments. We describe each of the three WTL assignments administered to students, and our study is focused on thematic analysis of students' responses to feedback surveys that elicited their cognitive and affective experiences with the assignments. Two research questions specifically guide this study:

1. How do organic chemistry students experience building connections between new concepts and their existing knowledge when responding to Writing-to-Learn assignments?
2. What components of Writing-to-Learn assignments do students perceive as supporting their learning of organic chemistry course content?

Theoretical framework

This research is guided by the aforementioned theories of meaningful learning, with additional attention to developing relevancy through authentic tasks (Bulte *et al.*, 2006; Stuckey and Eilks, 2014) and considering students' motivation for learning (Schunk, 1991; Vansteenkiste *et al.*, 2006, 2009). We posit that WTL assignments meet Ausubel's (1963) three requirements for meaningful learning while appealing to the learning domains in Novak's (1993, 2002) theory of human constructivism. As with any learning experience, the ability for WTL assignments to appeal to the elements of these learning theories is dependent on each assignment, the instructional context, and students' previous learning experiences. Nevertheless, the WTL assignments central to this study were designed with specific components meant to support students' meaningful learning. WTL assignments, in general, can be designed such that they require students to use their previous knowledge while exploring new concepts (Anderson *et al.*, 2015; Gere *et al.*, 2019). For example, an organic chemistry WTL assignment has the potential to help students transfer their existing knowledge of acid-base chemistry to their learning of the electron-pushing formalism. Furthermore, prior research has shown that WTL assignments can encourage students to connect new concepts to their prior learning (Finkenstaedt-Quinn *et al.*, 2017). Hence, we suggest that WTL assignments can be designed to provide the opportunity for students to choose to connect new information to their prior knowledge, thereby appealing to the cognitive learning domain.

In addition to appealing to the cognitive domain, WTL assignments can appeal to the affective learning domain by including rhetorical components meant to interest students by presenting authentic situations in which the content is relevant. Relevancy in science education, as described by Stuckey et al. (2013), contains three dimensions: the individual, societal, and vocational. Within WTL assignments, the connection of target concepts to specific contexts has the ability to appeal to one or more of these, dependent upon the individual learner and the context within the assignment. For example, an organic chemistry WTL assignment within the context of medicinal chemistry has the possibility to appeal to the societal domain by addressing the impacts of introducing new pharmaceuticals into society. Such an assignment could additionally appeal to the vocational domain for students interested in practicing medicine. The use of contexts within WTL assignments can thereby engage with both personal and societal dimensions, thereby moving beyond incorporating a context as a simple association between a single concept and a specific application. In this way, WTL assignments have the opportunity to appeal to the model of context-based curricula that focuses on social circumstances, which is theorized to most effectively incorporate context into conceptual learning (Gilbert, 2006). We posit that, through carefully selected rhetorical components, WTL assignments have the opportunity to appeal to the affective learning domain.

Relevancy and authentic tasks are closely related to students' motivation, which also relates to the affective learning domain. This is of particular importance, as students—and not instructors—are responsible for choosing to incorporate new knowledge into their existing knowledge framework. Prior research has used self-determination theory to characterize motivation for learning as rooted in motives that are either autonomous (i.e., by choice) or controlled (i.e., not by choice) (Vansteenkiste *et al.*, 2006). Studies have shown that students' motives—and the quality of their motivation—can be influenced by the teaching environment, such as the language used for assignments and instructions, the timeliness of feedback, and providing clear rationales for learning activities (Schunk, 1991; Vansteenkiste *et al.*, 2006, 2009). Each of these elements of the teaching environment are important considerations when implementing WTL assignments and are therefore valuable when considering students' experiences of WTL assignments. By interpreting students' experiences from completing the WTL assignments through theoretical perspectives of meaningful learning, relevancy through authentic tasks, and students' motivation, we can identify if and how the WTL assignments encourage students to engage in meaningful learning. Furthermore, these frameworks allow for insight into the specific assignment components and implementation structures that might support students' learning.

Methods

To address our research questions, we employed a qualitative design that allowed for a rich understanding of the range of students' meaningful learning experiences with the WTL assignments (Miles *et al.*, 2014). The qualitative design, in particular, complements the existing quantitative research on students' meaningful learning in organic chemistry (Galloway and Bretz, 2015a, 2015b, 2015c; Flaherty, 2020). To broadly examine students' meaningful learning experiences, the primary data source for this research is second-semester organic chemistry laboratory students' responses to open-ended feedback survey questions that were administered after the completion of each of the three WTL assignments. Semi-structured interviews conducted after each WTL activity served as a secondary data source to triangulate and corroborate the findings that emerged from analysing the feedback survey responses.

Setting and participants

This study took place at a large Midwestern research university in the January–April 2018 semester. Three WTL assignments were administered in the second-semester organic chemistry laboratory course, which included a weekly one-hour lecture and four-hour laboratory period. At this institution, the laboratory course is offered separately from the second-semester lecture course. The lecture course is a prerequisite/corequisite for the laboratory course. Historically, 84% of students take the lecture and laboratory courses simultaneously. In addition to the WTL assignments, students completed laboratory reports and took quizzes for assessment. The three WTL assignments contributed approximately 20% towards students' grades for the course. The participants for this study include the students enrolled in the course (N = 695), specifically those who opted to respond to optional feedback surveys (N = 333, 149, and 147, respectively for each assignment) and participate in interviews (N = 10, 9, and 8, respectively for each assignment). All students who participated in the surveys and interviews provided their informed consent, and Institutional Review Board permission was granted for this study.

Writing-to-Learn assignment design and implementation

The WTL assignments were designed and implemented with attention to the four essential characteristics for successful assignments as identified in Gere *et al.*'s (2019) review of WTL prompts: (1) engaging students in applying content-knowledge to a new task, (2) incorporating structures for peer interactions during the writing process, (3) supporting metacognition and reflection by requiring revision, and (4) setting clear expectations for what students should include in their writing. Each WTL assignment targeted different content areas to engage students' application of knowledge to new situations.

The first WTL assignment focused on acid-base chemistry. The prompt identified levothyroxine, a drug for treating hypothyroidism, and discussed how its effectiveness differs when interacting with different calcium supplements. Students were to assume the role of a medicinal chemist and to write an email to a physician with whom they were collaborating on a study about the co-administration of levothyroxine with calcium supplements. The objectives for the assignment were for students to describe how the levothyroxine molecule could act as a sodium salt, how a calcium ion could act as a Lewis acid, and why one calcium supplement would inhibit the absorption of levothyroxine but a different calcium supplement would not. These objectives require understanding the relationship between pH and pK_a and understanding how pH affects molecules' protonation states. The focus on acid-base chemistry was meant to reinforce the concepts students were formally introduced to in their prior organic chemistry experiences.

The second WTL assignment focused on a modified, base-free Wittig reaction and its substrate scope. The prompt described a base-free catalytic Wittig reaction and the implications for performing the reaction on an industrial scale in the production of chemicals such as vitamin A. Students were to assume to role of a science reporter for *Chemical and Engineering News*, and to write an article describing how the base-free Wittig mechanism related to the standard Wittig mechanism. In the article, students were also to discuss how the new reaction required no base and to discuss the limitations in substrate scope as identified within the prompt. The objectives for the assignment were for students to describe the traditional Wittig reaction, to determine the mechanism for a base-free modification of the Wittig reaction, and to discuss the substrate limitations for the base-free Wittig reaction. While students learned the traditional Wittig reaction during the lecture component of the laboratory course, this assignment was meant to encourage students to extend that knowledge by considering an alternative reaction that avoided the use of an external base.

The third and final WTL assignment focused on the reactivity of the drug thalidomide. This prompt described the history of the drug thalidomide being used as a sedative with harmful side effects. The assignment identified racemization and acid hydrolysis as mechanisms that affect thalidomide, and placed students in the role of an organic chemist writing a grant proposal about thalidomide analogues that would prevent these mechanisms. The objectives for this assignment were for students to describe the racemization and amide acid hydrolysis mechanisms for the thalidomide molecule, to propose an analogue that would prevent these mechanisms, and to explain how NMR could be used to monitor the progress of the hydrolysis reaction. This assignment was intended to relate broadly to the knowledge students should have been exposed to across their experiences in organic chemistry, including the concurrently taken second-semester lecture course. Specifically, the assignment was meant to reinforce the general mechanisms for racemization and acyl transfer reactions, both of which are formally taught in the second-semester lecture course.

The three assignments will hereafter be referred to as the acid-base, Wittig, and thalidomide assignments, respectively. The full text of each assignment is provided in Appendix 1. For each WTL assignment, students had one week to write their first draft, four days to complete the peer review process, and four days to revise and submit a second draft. Structures for peer interactions were provided by an automated peer review process in which each student read drafts and provided feedback to typically three peers. During the weeks the assignment components were open, students had the opportunity for further peer interaction with the course writing fellows. The writing fellows were undergraduate students who were previously successful in the course and trained to assist students with the content of the WTL assignments. The revision assignment after the peer review process provided time for students to revise their assignment after reflecting on their initial draft, peers' drafts they had read, and feedback they had received. Initial drafts and peer review comments were assessed for completion, and students were provided a rubric indicating the content areas that would be the focus of assessment for their final drafts. The assessment process was independent of the research reported herein.

Data collection

After the students turned in the second draft of each writing assignment, they were provided a link to a feedback survey. The survey asked students to respond to the following questions:

1. What do you like about this assignment? Please describe any aspects of the presentation or content of this writing assignment that were unclear.
2. What did you find the most challenging to write about?

Responding to the feedback surveys was not required, and students were not offered points toward their final course grade or other incentives for completing the feedback surveys. Of the 695 students enrolled in the course, 333 (48%) responded to the acid-base assignment feedback survey, 149 (21%) responded to the Wittig assignment feedback survey, and 147 (21%) responded to the thalidomide assignment feedback survey. All survey responses were included in the analysis. Additionally, semi-structured interviews (Herrington and Daubenmire, 2014) were conducted after students had completed all three components of each assignment (N = 10, 9, and 8 for the acid-base, Wittig, and thalidomide assignments, respectively). Students were recruited to participate in the interviews through a question at the end of the feedback surveys. These interviews were conducted as part of a larger research effort to understand students' responses and experiences with the WTL assignments. The interview protocol included some portions related to students' learning experiences, including questions such as "What did you learn by doing this assignment?" and "Is there anything that you found challenging to write about?" Each interview was audio recorded with the students' permission.

Data analysis

The feedback survey responses were qualitatively analysed with a coding scheme developed to characterize the students' meaningful learning experiences across all three WTL assignments. Codes were inductively developed for each question of the feedback survey for a single assignment. While researchers recursively coded the feedback survey questions for all three assignments, the coding scheme continued to be modified and developed (Miles *et al.*, 2014). After the initial development of the coding scheme, two researchers (TG and JSM) coded the same subset of responses and discussed their application of codes for each response (N = 60; 20 surveys from each assignment; 9.5% of the total surveys). Modifications were made to clarify the coding scheme, and a consensus was reached for the codes applied to these responses.

Two researchers (TG and JSM) then independently coded 20% of the feedback surveys not used in the development of the coding scheme and met to discuss the application of codes. Fuzzy kappa, a modified version of Cohen's kappa that allows for multiple codes to be applied to a single response, was calculated to determine the reliability of the coding scheme (Kirilenko and Stepchenkova, 2016). A fuzzy kappa value of 0.82 was calculated for the coding of students' responses to the first survey question, and a value of 0.85 was calculated for the coding of the second survey question. These values both indicate strong agreement among the two researchers (McHugh, 2012). Any disagreements for applying the coding scheme to individual responses were then resolved to reach a consensus for the final application of codes. One researcher (TG) then coded the remaining feedback survey responses.

The finalized coding scheme that was applied to all responses included two broad categories corresponding to students' responses to the two survey questions. The first category captures students' positive and negative affective experiences with the assignments, whereas the second category captures the challenges students had with the assignments. Each of these categories contains codes representing different aspects of students' meaningful learning experiences as elicited by the two feedback survey questions, and multiple codes could be applied to each response. After coding, the research team organized codes across both categories of the coding scheme into specific themes. The thematic analysis and the corresponding codes are presented in the Results. The frequencies of codes across survey responses to each assignment are presented alongside the complete coding scheme in Appendix 2, Table 3.

The interview data were used to corroborate findings related to the different meaningful learning experiences reported across the feedback surveys. As the interviews were used as a secondary data source to triangulate the primary feedback survey data, portions of the interviews related to the themes emerging in the feedback survey analysis were considered. All interviews were transcribed verbatim, then reviewed by the research team to identify excerpts of students describing their meaningful learning experiences. The research team then met to discuss the excerpts identified across all interviews and identify connections to the feedback survey analysis.

Results and discussion

The goal of this research is to characterize organic chemistry students' meaningful learning experiences with WTL assignments. To do this, we administered feedback surveys and conducted interviews to understand students' perceptions of the WTL assignments. Our analysis sought to understand how the assignments encouraged students to build connections between new concepts and existing knowledge. Furthermore, our analysis focused on the components of the WTL assignments and implementation that served to support students' meaningful learning with specific attention to the cognitive and affective learning domains. The results are organized by our two research questions. Each section is supplemented with excerpts from the feedback survey responses, while excerpts from the interview responses that corroborate each theme are provided in Appendix 3, Table 4.

RQ1: How do organic chemistry students experience building connections between new concepts and their existing knowledge when responding to Writing-to-Learn assignments?

Students reported that the WTL assignments encouraged them to make connections between new concepts and existing knowledge in different ways. This finding appeared in students' responses to both survey questions across the three assignments. Each WTL assignment appeared to support students' perceptions of how they built connections to existing knowledge in slightly different ways: via application of knowledge from previous courses, from the current course, and from a concurrent course. We captured these connections through the overarching theme *building connections between content*, and we have summarized the key sub-themes for this research question in Table 1. We will first describe the findings broadly relating to this theme, then we examine each assignment individually to illustrate the different ways students identified the assignments led them to connected new content to their existing knowledge.

Building connections between content. This theme encompasses instances of students describing how the assignments served to connect the new content presented within each WTL assignment to their existing knowledge. The most common responses were instances in which students described being challenged by writing about new concepts

Table 1. Sub-themes related to RQ1: How do organic chemistry students perceive building connections between new concepts and their existing knowledge when responding to the Writing-to-Learn assignments?

Sub-theme	Exemplar
Building on prior knowledge	*Acid-base feedback survey:* "I liked that this assignment helped reinforce the concepts learned in [Organic Chemistry 1] about acids and bases and their overall effect in a chemical reaction."
Building on course concepts	*Wittig feedback survey:* "What I liked about this writing assignment was that it pertained to the type of reaction that we had done in class."
Building on concepts from a concurrent course	*Thalidomide feedback survey:* "I liked how well it tied into what we were learning in [Organic Chemistry II Lecture]. It made it easy to understand why the mechanism proceeded in the way that it did."

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introduced by each assignment. Students finding the newly introduced concepts to be challenging provides evidence that the WTL prompts met their intended objectives of encouraging students to engage with new and challenging concepts through the writing process. Hence, the writing assignments appeared to successfully appeal to the cognitive domain required for a meaningful learning experience while providing tasks sufficiently challenging, which can support students' academic motivation (Vansteenkiste *et al.*, 2006). The feedback survey responses in which students indicated challenges with the conceptual material were closely examined to gain further insight for each prompt. From examining these responses, we found that the problems posed by each of the WTL assignments related to students' existing knowledge in slightly different ways: the acid-base assignment by connecting to students' knowledge from previous courses; the Wittig assignment by building upon students' knowledge gained in the laboratory course itself; and the thalidomide assignment by building on students' knowledge gained from the concurrent second-semester organic chemistry lecture course. These details demonstrate the range of ways in which writing assignments can engage students in applying their existing knowledge to new topics in a meaning-making task (Anderson *et al.*, 2015; Gere *et al.*, 2019). Each of the ways the assignments connected to students' prior knowledge are described in more detail below.

The remaining findings within this theme capture students' affective experiences regarding how the assignments helped them build connections between content. Some students indicated general positive feelings about how the assignments focused on developing their conceptual understanding. Other students indicated appreciating how they were required to draw from prior knowledge to address questions posed by the assignments. Students expressed mixed affective experiences about how closely aligned they found the assignments to the course. Each of these findings relate to how each assignment appealed to the affective domain of the learning experience and supported students in building connections to different types of existing knowledge. That students referred to the cognitive, conceptual components of the assignments with affective language contributes to prior research findings which suggested the inherent relationships between the cognitive and affective domains of meaningful learning (Galloway *et al.*, 2016).

Acid-base assignment: Building on prior knowledge. Students' feedback on the acid-base WTL assignment revealed that they perceived the need to know and apply their knowledge from previous chemistry courses. Students reported being challenged by each learning objective of the assignment, aligning with results from our previous work investigating the concepts that posed challenges for students on the same WTL prompt that was administered in the previous year (Schmidt-McCormack *et al.*, 2019). Many of the acid-base concepts that students reported challenges with, including difficulties with the relationship between pH and pK_a and defining or applying definitions of Lewis acids have been previously reported in the literature as challenging topics for students (Cartrette and Mayo, 2011; McClary and Talanquer, 2011; Stoyanovich *et al.*, 2015; Cooper *et al.*, 2016; Flynn and Amellal, 2016; Schmidt-McCormack *et al.*, 2019; Petterson *et al.*, 2020; Watts *et al.*, 2020).

Results from the feedback survey and interview analyses indicated that students perceived drawing upon their prior knowledge to complete the acid-base assignment. This use of prior knowledge is evident from instances in which students indicated, with positive affect, the need to use knowledge gained from other courses to formulate an answer to the assignment. For example, one student wrote,

> *I liked that it was a review of the things we have learned in [Organic Chemistry I Lecture], and we had to put different topics together in order to really answer the questions being asked.*

However, some students did not necessarily recognize that recall of prior knowledge was necessary for completing the assignment, finding the content irrelevant to the laboratory course:

> *It was also frustrating because it seemed that there were gaps between what has been taught and what we were supposed to know.*

The prevalence of students using prior knowledge to respond to the acid-base assignment was identified in the interview responses (e.g., the excerpt from Gabriella's interview in Appendix 3, Table 4). Similarly, some students not recognizing the connections to prior knowledge was also evident in the interviews (e.g., the excerpt from Matthew's interview presented in Appendix 3, Table 4). These responses suggest that some students found the assignment difficult because the content within the acid-base assignment was not directly related to the content they were currently learning. While this provides further evidence that the acid-base assignment required integration of previously acquired knowledge about acid-base chemistry, it also suggests that these conceptual connections between the organic chemistry courses were not explicitly clear to all students. This finding suggests that it is important to not only implement assignments that encourage meaningful learning by requiring students to connect to prior knowledge, but also to explicitly clarify the underlying and fundamental concepts. This is especially necessary for concepts from general chemistry that prior research on faculty perceptions suggests are important for students' success in organic chemistry (Duis, 2011).

Wittig assignment: Building on course concepts. The analysis of the feedback surveys after the second WTL assignment revealed that students found it to be challenging because of the way it extended ideas from the laboratory course itself. The concepts students primarily described as being challenging were related to two of the learning goals: how the modified Wittig reaction could function without a base and why acrylate would not participate in the modified Wittig reaction when the structurally similar maleate would. These challenges were reflected in the feedback survey responses; for example, one student wrote about needing to consider how the base-free Wittig reaction was both similar and different from the standard Wittig reaction the students performed in the laboratory:

> *I enjoyed thinking more about the reaction we learned about in class from a different angle. It was interesting to think about using no base, as well as various schemes that were similar to what we did in lab.*

Similar responses appeared in the interviews, in which students further expressed being challenged by the assignment's requirement to reflect upon and develop an account for why the base-free Wittig reaction works in some cases but not others (e.g., the excerpt from Jameson's interview in Appendix 3, Table 4). These challenges are reflective of the conceptual development expected to be elicited by case-comparison problems in organic chemistry (Graulich and Schween, 2018). This finding contributes to the literature by identifying that students experience the challenges intended by such problems.

The components of the assignment for which students indicated positive affect reflect how the assignment related to topics from the lecture and lab components of the course, where they were introduced to and performed the standard Wittig reaction. For example, one feedback response indicated:

> *I like that this assignment exposed us to things going on in the chemistry world today that are tied to the reaction we did in lab. I feel like we did not necessarily learn all the information we needed to answer the question posed in the writing assignment.*

However, as this response suggests, not all students valued that the assignment required them to extend their knowledge of the reaction performed in the laboratory to new situations. Despite this, other students indicated favouring the structure of the assignment, which first asked students about more familiar material (the traditional Wittig reaction) before asking students questions about new material (the modified Wittig reaction). For example, some students explicitly mentioned the way the assignment connected new material to what they were already familiar with:

> *I enjoyed the challenging aspect of the intramolecular mechanism present in the assignment. This made me apply what I already know to a new concept I was not too familiar with.*

This response aligns with prior research that suggests students are able to apply concepts they are familiar with to new material when responding to WTL assignments (Finkenstaedt-Quinn *et al.*, 2017). Furthermore, this finding contributes to our understanding of WTL assignments by identifying that some students recognize and value WTL assignments that require them to extend their existing knowledge. Overall, students' feedback on the Wittig assignment suggests how instructors can organize assignments to help students build connections between concepts in such a way that encourages them to recognize and choose to integrate new knowledge into their existing conceptual understanding.

Thalidomide assignment: Building on concepts from a concurrent course. Similar to the Wittig assignment, students also struggled with the new concepts that were presented by the thalidomide assignment. In the feedback survey analysis, students mentioned being challenged by each of the assignment's learning goals. For example, one student wrote about being challenged to determine the acid hydrolysis mechanism:

> *I found it rather difficult to come up with a mechanism for the acid hydrolysis products. It was difficult in that a student could come up with multiple mechanisms that worked, but had no particular hint as to why one mechanism may be favored over another.*

Students' abilities to describe the acid hydrolysis reaction mechanism are explained in our prior work, which demonstrates how some students, but not all, were able to connect explanatory concepts to the steps in the mechanism (Watts *et al.*, 2020). Additionally, students were challenged by the requirement to explain how the mechanism could be monitored by NMR. One student wrote:

> *For me the most challenging part was figuring out how to use NMR to determine the reaction progress. After realizing that it was the peaks that mattered, it made much more sense.*

This difficulty reflects prior research demonstrating students' challenges when reasoning about proton NMR spectra (Connor *et al.*, 2019). Our results indicate that students' perceived challenges for this assignment align with the intended challenges for the assignment, and extend the literature related to these concepts by identifying that students do perceive the inherent challenges.

Students' challenges with the assignment are reflective of the fact that the content addressed draws from concepts across the introductory organic chemistry curriculum. For instance, the acid hydrolysis mechanism was taught to students in the concurrent second-semester organic chemistry lecture course, and many students indicated this connection with positive affect. This is exemplified by a feedback survey response in which a student wrote:

> *I like that it made me use what I have learned in [Organic Chemistry II Lecture].*

However, other students were challenged by this component of the assignment, and it was evident that these students were not yet familiar enough with the reaction to recognize it in the context of the laboratory course. For example, one student wrote:

I like that this assignment was a little bit more unique and not just a summary of the experiments that we have done. However, some parts of it were confusing since we haven't directly addressed them in class.

This lack of familiarity was also described in the interviews (e.g., the excerpt from Madeline's interview in Appendix 3, Table 4). That not all students recognized the content within this assignment that was formally introduced in the concurrent lecture course highlights the essential role instructors have for designing instruction and assignments that explicitly connect to students' prior knowledge. Although the goal of this assignment was to relate to students' prior knowledge by asking them to describe a familiar mechanism and to build upon that knowledge by designing an analogue and discussing NMR, it was evident that some students did not recognize the acid hydrolysis mechanism in the context of the assignment. This lack of recognition suggests the importance of assignment features to help students recognize these connections.

RQ2: What components of the Writing-to-Learn assignments do students perceive as supporting their learning of organic chemistry course content?

Information about the assignment components that support students' meaningful learning was present in the coding for all feedback survey questions. The findings are presented as the themes identified during the analysis: specifically, how the assignment supported students' meaningful learning by (1) *encouraging problem-solving*; (2) *including specific rhetorical components*; (3) *having clear expectations, support, and resources*; and (4) *engaging students in the peer review process*. These themes are summarized in Table 2 and described in detail below, with identification of how different assignment components supported students' meaningful learning.

Encouraging problem-solving. This theme includes instances where students described perceiving that the WTL assignments required them to engage with the problems posed by the assignments. The theme is characterized by students indicating the way the assignments required them to solve problems with thought and creativity. For example, one student responded to the acid-base assignment feedback survey with:

I liked that there was a lot of autonomy to the paper that allowed me to talk about multiple scenarios for the acid base reaction.

Other students indicated disliking the challenging nature of the assignments; for example, one student's survey response after the acid-base assignment included:

It was overall very challenging which is good to a point but I think it was too challenging.

Students made similar comments about the prompts encouraging problem-solving within the interviews, as exemplified by the excerpt from Lesley's interview in Appendix 3, Table 4. This theme provides further support for the interconnections between the cognitive and affective domains of learning experiences (Galloway *et al.*, 2016). Additionally, this theme captures the mixed affect students felt about being challenged by the assignments. Students' varied experiences with valuing how the WTL assignments encouraged problem solving highlights how students' affectual experiences depend on the individual students, as suggested in prior research (Galloway and Bretz, 2015b, 2015d; Hensen *et al.*, 2020). Furthermore, that some students valued tasks that challenged them to solve problems aligns with the literature on the quality of students' academic motivation, particularly in how such tasks can support students' autonomous motivation (Vansteenkiste *et al.*, 2009). Overall, this theme suggests that the problems posed by assignments, and the different levels of difficulty for different students, influences students' affective learning experiences. This finding extends the prior research suggesting the inherent relation between students' attitudes and their motivation towards learning (Grove and Bretz, 2012).

Including rhetorical assignment components. The assignments' rhetorical components include the genres in which students were constructing their responses, the audiences to whom students were writing, and the context in which they were

Table 2. Themes related to RQ2: What components of Writing-to-Learn assignments do students perceive as supporting their meaningful learning of organic chemistry course content?

Theme	Exemplar
Encouraging problem-solving	*Thalidomide feedback survey:* "I thought the assignment was quite engaging and required me to learn more about racemization and acid hydrolysis that I had not known previously."
Including rhetorical assignment components	*Acid-base feedback survey:* "I liked the context for this assignment. I thought that rather than writing an essay/short response, writing an email to a 'colleague' helped broaden my writing style and was much more interesting to do."
Providing clear expectations, support, and resources	*Wittig feedback survey:* "I like that the instructions are detailed and well written so that we know what questions to answer when thinking about our response. It really helps narrow down which information to include."
Engaging students in the peer review process	*Acid-base feedback survey:* "While it kind of feels like a hassle to have to review three other writing assignments, I enjoyed it much more than I expected to. Reviewing the other assignments helped me to understand the concepts of the problem more than I previously had, and being able to read the revisions for my assignment made me feel more confident in the work I had done/more certain about the work that still needed to be done."

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providing their responses. The prompts' connections to authentic applications appeared within students' responses in a variety of ways, including indications that the assignments helped them to identify why the organic chemistry content might be useful to fields of interest for potential future careers. This is exemplified by a response to the acid-base assignment feedback survey:

> *I liked the application of my organic chemistry knowledge to pharmaceuticals and biochemistry. I am interested in these fields, and it was great to understand some aspects of such a complex field.*

Similar comments about relevance were made about all three assignments, as each dealt with a practical scenario in some way. For example, a representative response from the thalidomide assignment feedback survey indicated recognizing the practicality of the organic chemistry content:

> *I liked hypothesizing different forms of thalidomide that might prevent the teratogenic effects. It was nice seeing practical implications of our chemistry work.*

These sentiments were also present within the interviews, as seen in the excerpt from Jessie's interview provided in Appendix 3, Table 4. Students' recognition of the different ways the content of each assignment was relevant to them illustrates how WTL assignments can appeal to a mixture of the individual, societal, and vocational relevance domains (Stuckey *et al.*, 2013). Furthermore, this finding suggests that the WTL assignments successfully incorporated context within assignments that students generally perceived to also support their conceptual learning. This illustrates how assignments implemented throughout the semester can serve to incorporate authentic contexts in ways similar to context-based curricula (Gilbert, 2006; Pilot and Bulte, 2006).

Some students found the other rhetorical components of the WTL assignments, specifically framing their essay for the appropriate audience and writing within a specific context, more challenging. These experiences reflect challenges with balancing the level of detail with which they were expected to write about concepts. For example, one student's feedback survey indicated:

> *I found it challenging to work through an entire process and describe it all in paper step-by-step. I can understand it myself, but writing it down makes it more complicated because I do not realize when something needs an explanation and when it does not.*

While students found it a challenge to balance the depth of explanation for particular concepts, this reflects the learning goal for the assignments to engage students with content by constructing explanations. Altogether, these responses provide evidence that the rhetorical assignment components that connect the chemistry content to authentic situations did not necessarily interfere with the primary learning objective of the WTL assignments, but rather served to promote some students' interest and engagement. Stimulating interest is necessary for supporting meaningful learning in that students' interest is inherently tied to their motivation for actively incorporating new knowledge into their existing conceptual frameworks (Ausubel, 1963; Schunk, 1991; Vansteenkiste *et al.*, 2006).

Providing clear expectations, support, and resources. Several students described challenges and positive or negative affective experiences surrounding the expectations, support, and available resources for the assignments, relating to the necessity for successful WTL assignments to provide clear expectations (Anderson *et al.*, 2015; Gere *et al.*, 2019). Negative affective responses to the feedback surveys reflected what students found unclear about the assignments, though these responses were balanced by students who indicated, with positive affect, that the assignments were clear. These students discussed clarity in terms of both assignment directions and content-specific prompt components. For the assignment directions, students specifically reported finding the acid-base assignment, but not the other two assignments, unclear with regard to the level of detail they were supposed to include in their writing. For example, one student responded to the acid-base feedback survey saying:

> *However, the prompt and general directions for this writing assignment were unclear, and the expectations were not outlined clearly—it was hard to know what to write about, and what was expected of us.*

The interview analysis revealed that this sentiment, for some students, arose from the lack of a clear list of expectations enabling them to know what to include in their response (e.g., the excerpt from Gabriella's interview in Appendix 3, Table 4). The lack of clarity from the students' perspective might also be related to the language in the assignment, how the assignment was introduced to students, or the fact that the acid-base assignment was the first WTL assignment. The distinction between these possibilities were not evident in our analysis but would be worthy of future research. Nevertheless, students' feedback echoes the sentiment that clear expectations for writing are necessary for effective WTL assignments (Anderson *et al.*, 2015; Gere *et al.*, 2019). Furthermore, our findings about students' experiences with the assignment expectations is necessary to understand for future implementations of WTL assignments, as elements of the teaching environment surrounding the expectations for students are known to influence students' academic motivation (Schunk, 1991; Vansteenkiste *et al.*, 2006).

The feedback survey responses identifying that the Wittig and thalidomide WTL assignments were unclear more closely linked to content rather than the assignment directions. For example, a comment from the Wittig feedback survey indicated that the student was not sure about directions expressly asking them to explain the role of a specific reactant:

> *I think that the wording of the 3rd checklist point in the prompt (The role of PBu_3 in Scheme 2 should be explained) was vague and hard to understand—I had to clarify it with a writing fellow.*

Similarly, for the thalidomide assignment, students expressed that the expectations for proposing an analogue were not clear:

> *It's not clear what is close enough to thalidomide to be an analog.*

In these cases, students appeared to be aware of the assignment expectations themselves but were unsure about how to respond to the questions posed by the assignments.

Some students also wrote about the assignments being challenging because they required them to utilize resources—including peers, writing fellows, or instructors—to complete the assignments. These reports provide evidence that the challenges students had with the assignments promoted social interactions during the writing process, another component of successful WTL assignments (Anderson *et al.*, 2015; Gere *et al.*, 2019). Other prompt features that students wrote about in their feedback survey responses with less frequency include the figures, word limit, expectations for citations, and time required to respond to the assignments. As the range of comments associated with assignment expectations suggests, the various expectations, support, and resources surrounding the assignment are as important for creating meaningful learning experiences as the content and rhetorical components of the assignments. These findings corroborate previous research suggesting that clear writing expectations for students are vital in engaging students in meaningful writing experiences (Anderson *et al.*, 2015; Gere *et al.*, 2019). Furthermore, this finding extends research indicating how the teaching environment—particularly clear directions and availability of support—influences the quality of students' motivation and their affective experiences (Vansteenkiste *et al.*, 2009).

Engaging students in the peer review process. Students indicated both positive and negative affective experiences with the peer review process. This theme was most prevalent in students' feedback responses to the first WTL assignment, but the topic came up in interviews for all assignments (e.g., the excerpt from Stephen's interview in Appendix 3, Table 4). Students generally discussed the value of peer review and how it helped them with the assignments. Comments about the peer review process included that both receiving and providing feedback helped them understand the content in the assignment better. As indicated by one student's response to the thalidomide feedback survey:

> *I like the unique approach of having other students comment on your assignment. This helps if you were mistaken in some concept because students can practice identifying errors and the one making the error can correct it.*

Participating in the peer review process provided students with the reassurance that they included correct conceptual information in their written responses, thereby engaging students in both the affective and cognitive domains of meaningful learning. This finding also suggests the importance of peer review for providing students with peer models and timely feedback, both of which are suggested to enhance students' academic motivation (Schunk, 1991; Vansteenkiste *et al.*, 2006). Students ascribed value to both receiving and providing feedback, corroborating related studies that likewise examined the role of each component of the peer review process (Lundstrom and Baker, 2009; Cho and Cho, 2011; Cho and MacArthur, 2011). Furthermore, that students reported being able to successfully engage with concepts during peer review extends the results from prior studies that found students to do this through analysing students' writing and peer review comments (Finkenstaedt-Quinn *et al.*, 2017, 2019, 2020; Halim *et al.*, 2018; Moon *et al.*, 2018).

While many of the students who mentioned peer review did indicate finding the peer review process helpful, a small number reported finding the process unhelpful or challenging. For example, one student expressed not receiving any constructive criticism from the peer review for the acid-base assignment:

> *…I also wasn't very happy with the peer review; some of my reviewers were rude and unhelpful, and no constructive criticism was given.*

Generally, students indicated finding peer review unhelpful when reviewers gave non-constructive feedback or when students received conflicting sets of feedback. Future research should seek to understand ways to support students in providing constructive feedback and to support students' ability to provide constructive feedback and to respond to feedback that is conflicting or not constructive. However, the peer review process generally has been shown to have positive effects for students, even when compared to receiving feedback from content experts (Cho and Schunn, 2007; Patchan *et al.*, 2009; Cho and MacArthur, 2010; Zhang *et al.*, 2017). Our findings suggest that, although some students may have negative experiences with peer review, many students have positive experiences and the implementation of peer review nevertheless provides the structures for peer interactions that support motivation and encourage reflection and revision (Schunk, 1991; Anderson *et al.*, 2015; Gere *et al.*, 2019).

Conclusions

This study presents a qualitative analysis of students' feedback survey responses for three WTL assignments that were implemented in an organic chemistry laboratory course to enhance students' meaningful learning experiences. This research provides the first step in understanding the utility of WTL assignments to facilitate students' meaningful learning experiences within organic chemistry laboratory courses by (1) identifying varied ways that WTL assignments can connect new concepts to students' prior knowledge and (2) identifying how components of WTL assignments and implementation can support students' learning experiences. This research was conducted through the lens of meaningful learning theories, with attention to the literature on developing relevancy through authentic tasks and considering students' academic motivation. This is necessary because research in the chemistry education literature has identified that students' approach to learning is closely related to their perceptions of the course and its relevance (Grove and Bretz, 2012; Galloway *et al.*, 2016). While faculty often seek to emphasize the relevance of course material through laboratory components of chemistry courses, there appears to be less focus on affective goals for instruction in organic chemistry and other advanced chemistry laboratories (Bretz *et al.*, 2013). By presenting necessary insight into students' perceptions of a pedagogy that is designed to support students' affective experiences, Writing-to-Learn, this study extends the research on organic chemistry students' meaningful learning experiences.

Findings from this study indicate that the WTL assignments implemented in the second-semester organic laboratory course successfully provided students with opportunities for meaningful learning. Students perceived the three assignments to connect to their prior knowledge in slightly different ways: (1) by connecting to ideas from previous courses such as general chemistry and first-semester organic chemistry, (2) by connecting to ideas from the second-semester laboratory course itself, and (3) by connecting to ideas from the concurrent second-semester lecture course. In these ways, the assignments appealed to the cognitive domain of meaningful learning by requiring students to draw from knowledge from both previous and concurrent courses. In particular, students perceived the content of the prompts to challenge them to build connections to their existing knowledge of topics ranging from acid-base chemistry to reaction mechanisms.

The assignments also appealed to the affective domain necessary for meaningful learning by encouraging problem-solving; including rhetorical components that emphasized the relevance of the content; having clear expectations, support, and resources; and incorporating peer review. Our findings relating to each of these themes indicate an interplay between the cognitive and affective domains. Additionally, students' affective experiences appeared to be fostered by the rhetorical framing of each assignment within authentic contexts. Students found these contexts to be relevant to their lives and career goals. Importantly, students generally did not find writing within particular rhetorical contexts to be difficult beyond the challenge of communicating content knowledge, thereby allowing students to grapple with content rather than context. Students' affective experiences were also found to be influenced by the clarity of expectations. Specifically, our results suggest that clear expectations can serve to improve students' affective engagement with the assignments and, when unclear, can hinder engagement. Lastly, the incorporation of peer review generally enhanced students' experiences with the assignments by providing reassurance or guidance about their conceptual understanding. These findings illustrate how the specific components of WTL assignments can influence students' affective experiences through creating experiences that emphasize relevancy while supporting academic motivation.

Limitations

There are several limitations associated with this study. First, this study was completed at a research-intensive institution in the United States, and the findings may not be transferrable to populations of students at other institutions. Additionally, students were not provided any course credit or incentive for responding to the feedback surveys. The lack of incentive could be responsible for the higher survey response rate for the first assignment in relation to the lower response rates for the last two assignments. It could also be a source of self-selection bias, as students may have been more likely to respond if they had strong opinions. The students participating in interviews were also selected on a voluntary basis, which could also have contributed to self-selection bias. Hence, the results from the feedback survey and interview analysis may not be representative of the entire organic chemistry course population at the institution. Furthermore, the feedback survey questions were broad, open-ended, and not directly aligned with the meaningful learning theories, meaning that students may not have provided a complete depiction of their meaningful learning experiences in their responses. Another limitation is that quantitative measures of meaningful learning were not administered to students either before or after completing the WTL assignments. Furthermore, no comparison groups were included. Hence, the results from this study cannot indicate whether students' expectations for meaningful learning in the organic chemistry laboratory course were influenced or fulfilled by completing the WTL assignments. For these reasons, the results of this study are limited in scope to qualitatively identifying aspects of WTL assignments that influence organic chemistry students' meaningful learning experiences rather than measuring students' meaningful learning experiences.

Implications

Implications for research

This study demonstrates utilizing the theoretical lens of meaningful learning to qualitatively investigate students' experiences with WTL activities. Chemistry education research has largely focused on quantitative studies of meaningful learning (Flaherty, 2020), and it is valuable to employ qualitative methodologies to better understand students' experiences. Future research could similarly employ qualitative methodologies to make sense of students' meaningful learning experiences within other curricula or in response to other pedagogical interventions. Because the present study primarily relied on open-ended survey responses with supplementary interview data for triangulation, future qualitative research on WTL pedagogies could additionally employ alternative methodologies, such as the word lists meant to elicit affective responses used by Galloway *et al.* (2016), to ascertain a more comprehensive view of students' experiences with WTL assignments. Studies should also be conducted that employ mixed methods to understand students' experiences qualitatively while quantitatively measuring students' meaningful learning in response to pedagogical interventions, using instruments such as the MLLI. Future research could also more directly examine the role that instructors, including the course instructor, teaching assistants, and undergraduate writing fellows, have in contributing to students' meaningful learning experiences with WTL assignments. For instance, prior research by Flaherty *et al.* (2017) suggests that when graduate teaching assistants were trained in a meaningful learning pedagogy, the number and quality of interactions between the teaching assistants and students increased. Similar research should be conducted for pedagogical interventions, including WTL, that are specifically designed to support students' meaningful learning experiences.

Implications for practice

This study suggests that instructors should set clear learning goals when designing writing assignments and should be intentional when considering how new concepts targeted by writing assignments will connect to students' existing knowledge. Our findings suggest that students recognize the elements of writing assignments that are necessary for meaningful learning experiences, particularly how assignments explicitly connect to their knowledge from prior courses, knowledge from the course in which the assignment is given, or knowledge from courses taken concurrently. These findings also imply the recommendation that instructors incorporate rhetorical framing within an authentic context and include structures such as peer review and revision when designing and implementing writing assignments. Students' engagement with authentic contexts and peer review can support both the affective and cognitive domains of the learning experience. Furthermore, this research suggests that clear expectations within the writing assignment are recognized by students and can likely influence their meaningful learning experiences. The rhetorical prompt components and clarity of expectations can influence students' engagement with the assignments, if and how they build connections between concepts, and if students find the assignments relevant or motivating. Details of assignments, such as the presentation of figures, the requirement and format of citations, and the directions provided within assignments, all influence students' experiences with the assignment. By carefully attending to each detail of assignments, instructors can influence students meaningful learning experiences and thereby encourage students to engage in the process of incorporating new knowledge and ideas into their existing knowledge framework.

Conflicts of interest

There are no conflicts to declare.

Appendices

Appendix 1. Full text of the three Writing-to-Learn assignments.

Acid-base WTL assignment

Levothyroxine, which is used to treat hypothyroidism, is less effective when taken in combination with calcium carbonate. In contrast, calcium citrate, which is also an over the counter calcium supplement, causes little or no interference with the absorption of levothyroxine by the body (Figure 1).

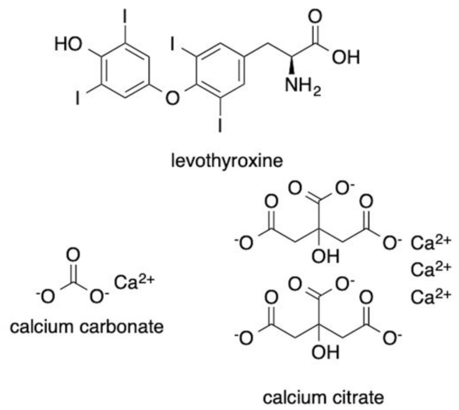


Figure 1. Acid-base assignment figure.

For this assignment, you'll take the role of a medicinal chemist writing an email to a collaborator, who is a physician-researcher planning a clinical trial. The goal of the trial is to investigate the co-administration of levothyroxine with calcium supplements. The physician, who took organic chemistry several years ago, has requested your help to clarify the interactions between molecules like levothyroxine and other drugs.

Specifically, your collaborator needs to understand how neutral levothyroxine is deprotonated to its sodium salt form, which is more absorbable in the body. They also need to know how Ca^{2+} as a Lewis acid may interact with levothyroxine to prevent its absorption. Finally, the physician should understand why Ca^{2+} in calcium carbonate may interact with levothyroxine and prevent its absorption whereas Ca^{2+} in calcium citrate will not.

Items to keep in mind:

- This should be an email of between 500–700 words.
- Be sure to explain the relative acidity of each site on levothyroxine and which site would be deprotonated first to make the sodium salt—the form that is given to patients.
- Consider the pH of the stomach acid (1.5 to 3.5) when predicting the predominant Levothyroxine species.
- Remember to appropriately format your email as a letter with a salutation, closing, and proper paragraphing.
- Since you are imagining that you are writing to a colleague, carefully edit and proofread your essay to maintain credibility and consider, as a medicinal chemist, how you would write to an audience in a different field.

Wittig WTL assignment

Recently a research article was published reporting the first base-free catalytic Wittig Reaction. The finding has important implications for industry because the Wittig reaction can be used to make important chemical products on an industrial scale. For example, BASF (the world's largest chemical company) began using the Wittig reaction as a key step in the production of ß-carotene (vitamin A) in the early 1960s. The general Wittig reaction is shown below in Scheme 1, followed by a successful example of the new Wittig reaction from this publication in Scheme 2 (Figure 2).

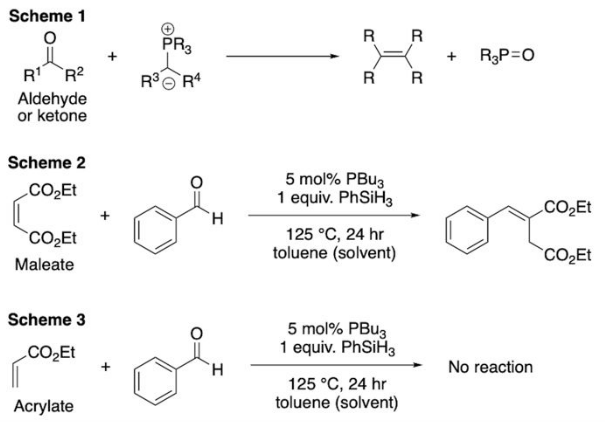


Figure 2. Wittig assignment reaction schemes.

You are a science reporter who regularly contributes short pieces that highlight important chemistry discoveries to *Chemical and Engineering News* (C&EN), which is the premier magazine of the American Chemical Society. This research article captured the attention of your editor at C&EN, and she has assigned you to write a highlight about the chemistry described in the study for the upcoming issue of the magazine.

The challenge of highlighting research for C&EN is the wide range of its readership, which includes ~160,000 members who are either professional chemists, chemistry students, or persons in areas that may relate to chemistry and work in academia, industry, non-profits, or policy. Their specialties are wide-ranging and include fields like biochemistry, chemical engineering, inorganic chemistry, medicinal chemistry, or even physics (to name a few). This means that each reader will have some general proficiency in chemistry, but that you should not assume a depth of understanding in organic chemistry. Be sure to translate any organic chemistry jargon or terms for the reader. Use a style and language that is accessible to the broad readership of the magazine. Also keep in mind that it is a news magazine so you should have a catchy title and feel free to take some creative license in your writing to make it more engaging.

Your article should be approximately between 350-750 words in length. In writing your article you must address the following points:

1. Explain the key mechanistic steps that lead to this transformation. Focus specifically on the formation of the ylide in scheme 2. Note that the ylide that is ultimately formed is not shown in this scheme.
2. Explain why no base is needed in scheme 2 and contrast with the general Wittig reaction in scheme 1.
3. Explain the role of PBu_3 in the reaction and why it can react with a functionalized alkene (maleate) instead of an alkyl halide (the standard reaction pathway shown in class). You do not need to discuss the role of $PhSiH_3$ in your draft; the $PhSiH_3$ acts as a reducing agent to regenerate PBu_3.
4. Stress the key aspects of the reaction that make it attractive for industrial scale reactions.
5. Offer an explanation as to why the product is formed in *E/Z* ratio 96/4.
6. Address the limitation (Scheme 3) that the reaction does not work with acrylates. (Offer an explanation as to why this is so).

Thalidomide WTL assignment

Thalidomide was widely used after World War II as a sedative and later as a treatment for morning sickness. Unfortunately, it was only after widespread use that it was discovered that thalidomide causes very serious side effects – in particular, birth defects such as phocomelia (limb malformation). The drug was banned in 1962 and these events resulted in important changes to the way the FDA approves drugs.

Despite the inherent dangers, thalidomide is now used for treatment of serious diseases, such as cancer and leprosy, when the benefit of treatment outweighs the inherent risks. It is now understood that thalidomide exists as two enantiomers; one is a teratogen and the other has therapeutic properties. Rapid racemization occurs at body pH and both enantiomers are formed at roughly an equal mixture in the blood, which means that even if only the useful isomer is used, both will form once introduced in the body. Furthermore, both enantiomers are subject to acid hydrolysis in the body and produce hydrolysis products that may or may not be teratogens depending on their structure. The structure of thalidomide and two thalidomide hydrolysis products are shown below in Figure 3.

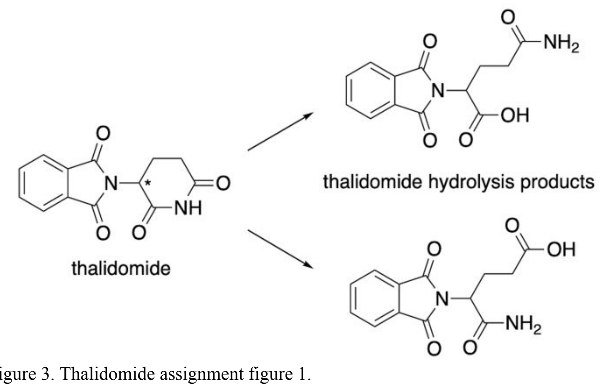
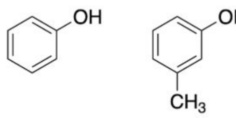


Figure 3. Thalidomide assignment figure 1.

You are an organic chemist collaborating with a team of other researchers from the University of Michigan with the goal of testing thalidomide analogs for cancer treatment. An analog is a compound that is very similar to the pharmaceutical target that has small structural differences. For example, m-cresol (shown in Figure 4 below) is an analog of phenol.

Your goal will be to design a structural difference that will make the thalidomide analog less reactive toward hydrolysis than thalidomide. Your analogs will be tested for the inhibition of a pro-inflammatory protein mediator, which in elevated levels may be responsible for symptoms associated with the early stages of HIV.



phenol *m*-cresol

Figure 4. Thalidomide assignment figure 2.

Although thalidomide is warranted for treatment of some diseases, it would be preferable to identify an analog that has similar therapeutic qualities without the potentially devastating side effects. It is known that thalidomide is easily hydrolyzed, and it has been proposed that one of the biologically active species may be one of the two possible hydrolysis products shown above in Figure 3. Thus it is important to propose analogs that are not readily hydrolyzed.

Your research team is drafting a grant proposal for the National Institute of Health. You must contribute between a 350–750 word description explaining the structure and reactivity of thalidomide toward hydrolysis and the structural differences in proposed analogs that will make them inert to hydrolysis. Set the tone of your piece by placing your description in the context of the larger goal of developing a safer drug for the treatment of cancer patients. The committee who will review the proposal is likely to be made up of scientists from disciplines including biology, chemistry and medicine. While they are experts in their own field, they may not be knowledgeable about organic chemistry, racemization, hydrolysis, or NMR spectroscopy. You should consider carefully which organic chemistry terms you use and when you define or explain them. Remember, your collaborators are relying on you to clearly communicate your plan so that they can write a competitive proposal for funding from the NIH.

When writing, you should consider the following:

1. Explain the mechanism for acid hydrolysis of thalidomide to form the two hydrolysis products in Figure 1.
2. Design one compound (thalidomide analog) that should be a pro- inflammatory protein mediator inhibitor. Explain. Keep in mind that any changes to the structure of a molecule can result in vastly different activity in the body.
3. Explain why it is important that thalidomide analogs do not have acidic protons at their stereocenters.
4. Describe how you would monitor hydrolysis of thalidomide by NMR.
5. Be sure to cite any outside sources that you used while writing your paper. Images that you did not draw yourself must have the original source cited. Sources should be cited using the APA/ACS format.

NOTE: You can choose to include drawings of either the mechanism or of your proposed analog. However, given your audience, your written explanation should be sufficient such that your proposed analog can be understood without the drawing.

Appendix 2. Complete coding scheme.

Table 3. Complete coding scheme.

Code (Survey Question)	Definition	Exemplar	Frequency, Acid-base (N=333)	Frequency, Wittig (N=149)	Frequency, Thalidomide (N=147)
Theme: Building connections between content					
New concept (Q2)	The student indicated being challenged by new concept introduced by the assignment.	"The hardest part was figuring out why the reaction doesn't need a base and figuring out that there must be a proton rearrangement that goes on."	228	110	120
Conceptual understanding (Q1, +)[a]	The student indicated feeling that the assignments helped them develop conceptual understanding.	"The assignment challenges me to understand the organic chemistry concepts and articulate them properly/clearly."	16	19	10
Relevant to class (Q1, +)[a]	The student indicated that the assignment material related to the course content.	"I liked this assignment because it was related to what we were doing in lab and seemed more relevant than [the acid-base assignment]."	70	37	20
Not relevant to class (Q1, -)[a]	The student indicated feeling underprepared to respond to the assignment based on the course content.	"The presentation was pretty clear but we were not equipped with insight from lecture to know how to answer the questions."	22	11	13
Prior knowledge (Q1, +)[a]	The student indicated drawing from previous knowledge and applying it to	"It brought a reaction which was talked about in [Organic Chemistry I Lecture] (hydrolysis) and connected it to	30	3	1

	new situations.	[Organic Chemistry II Lecture and Laboratory] material."			
Theme: Encouraging problem solving					
Problem-solving (Q1, +)[a]	The student indicated feeling satisfied by the problem-solving required to complete the assignment.	"When I was able to make sense if an unknown reaction I was very satisfied."	62	38	45
Thought-provoking (Q1, +)[a]	The student indicated that the assignment was thought-provoking.	"I liked that it required thought outside the actual lab pages results."	45	33	23
Creative (Q1, +)[a]	The student indicated feeling satisfied by the assignments supporting their creativity.	"The assignment allowed us to be creative while still learning chemistry along the way."	16	13	15
Challenging (Q1, +)[a]	The student indicated feeling challenged by the assignment in a productive way.	"I liked the challenge of considering the pK_a of several molecules in order to explain how they interact."	1	5	1
Challenging (Q1, -)[a]	The student indicated feeling challenged by the assignment in an unproductive way.	"At first I thought it was hard to approach, and without office hours I would be very lost on how to answer some questions."	16	5	12
Easy (Q1, +)[a]	The student indicated finding components of the assignment easy to complete.	"The mechanism was pretty obvious, as were the changes that would be observed in the H NMR"	1	3	3
Theme: Rhetorical assignment components					
Relevance (Q1, +)[a]	The student indicated feeling that the assignment related content to a practical, authentic situation.	"I also liked how the assignment asked us to relate this new reaction to real-life industrial applications."	31	40	31
Audience (Q2)	The student indicated being challenged by writing to the designated audience.	"At first, I also struggled with organizing my email for a person not in organic chemistry to better understand."	22	7	2
Context (Q2)	The student indicated being challenged by the level of detail with which they were expected to write about concepts.	"I found it challenging to work through an entire process and describe it all in paper step-by-step. I can understand it myself, but writing it down makes it more complicated because I do not realize when something needs an explanation and when it does not."	72	31	29
Theme: Providing clear expectations, support, and resources.					
Clear (Q1, +)[a]	The student indicated that the assignment (or part of the assignment) was clear to them.	"The goals of the writing assignment and the questions asked about it were clear."	66	25	17
Unclear (Q1, -)[a]	The student indicated that the assignment (or part of the assignment) was unclear to them.	"The only thing that was a little unclear at first was considering why one product was major over the other one."	92	25	45
Prompt directions (Q2)	The student indicated being challenged by the directions in the prompt.	"It was very challenging to figure out exactly what each question was asking and to answer it in the way that they wanted."	35	16	14
Outside help (Q2)	The student indicated needing to utilize resources to complete the assignment,	"I thought that it was very difficult to come up with the ideas by myself or through research, only after talking it	31	17	12

	including internet searches or seeking help from graduate student instructors, writing fellows, or peers.	through with friends did I understand what was going on."			
Figure (Q1, +)[a]	The student indicated finding the figures helpful.	"I liked that the schemes were included in the prompt; it made it a lot easier to understand the differences between each."	1	7	3
Figure (Q1, -)[a]	The student indicated problems with reading the figures.	"I did not like how the diagrams given were blurry and difficult to read."	1	3	0
Word limit (Q1, -)[a]	The student indicated feeling constrained and/or challenged with the word limit.	"Not much about the situation/prompt was unclear, but I was unsure about the word count, since it was 'approximately 350-750' words. Does that mean that we cannot write more than that? Or is it acceptable if we write close to that range?"	3	1	1
Citing (Q1, -)[a]	The student indicated problems with providing citations.	"For the first draft, it was unclear what images needed to be cited."	2	3	1
Time (Q1, -)[a]	The student indicated feeling the assignment took more time than was needed.	"I did feel that the assignment was a little bit of a waste of time. I felt that my time was needed in other ways for my success in this class."	6	5	5
Theme: Engaging students in the peer review process					
Peer-review (Q1, +)[a]	The student indicated feeling that the peer-review process was helpful.	"I thought that the peer revision phase of this assignment was really helpful in making sure I got my ideas across."	81	4	8
Peer-review (Q1, -)[a]	The student indicated feeling that the peer-review process was unhelpful.	"I also wasn't very happy with the peer review; some of my reviewers were rude and unhelpful, and no constructive criticism was given."	8	1	0
Peer-review (Q2)	The student indicated challenges with the peer-review process.	"...the peer reviews that I read and received all had different understandings of the prompt. I also found it challenging to translate my peer review feedback into my revisions because I received three very different sets of feedback... getting very polar feedback created a challenge for me."	16	2	2

[a]Codes with a "+" applied to responses with positive affect, while codes with a "-" applied to responses with negative affect.

Appendix 3. Interview excerpts.

Table 4. Interview responses relating to themes that emerged from the feedback survey analysis.

Theme	Exemplar
Themes related to RQ1: How do organic chemistry students perceive building connections between new concepts and their existing knowledge when responding to the Writing-to-Learn assignments?	
Building on prior knowledge	*Gabriella, acid-base assignment interview:* "...it made a pretty good review of [Organic Chemistry I Lecture] ideas going into [Organic Chemistry II Lecture, because this was assigned during just the very beginning." *Matthew, acid-base assignment interview:* "...it felt like out of left field. We weren't doing this in lab. We hadn't done this in [Organic Chemistry II] lecture. It was just really random. I'll write about it, because I kind of know what I'm talking about, but at the same time..."

Building on course concepts	*Jameson, Wittig assignment interview:* "This is something definitely I should have been able to figure out but it's not like, you know, like a sort of stale question. Like, okay, what is the Wittig reaction or blah, blah, blah. Because you can just copy that out of your notes. So these were the two questions. . . that actually we had to sort of think and say okay, well, we have to use our logic here and see, okay, why wouldn't there need to be a base. Or, why won't this reaction work in this situation?"
Building on concepts from a concurrent course	*Madeline, thalidomide assignment interview:* "...for this assignment… I couldn't tie it to one lecture that we took in class or something we did in lab. I don't know why. I know we did it, but it was ... I think the other assignments were pretty straightforward, like they have the same title as the lab that we're doing in class."
Themes related to RQ2: What components of Writing-to-Learn assignments do students' perceive as supporting their meaningful learning of organic chemistry course content?	
Encouraging problem-solving	*Lesley, thalidomide assignment interview:* "I thought it was kind of interesting, it was almost like a puzzle, figuring out how can you change this to halt the process. That was a new way to look at, to examine a reaction. How you can prevent the reaction from going past a certain point. What can you do to stop that? It made me look at reactions in a slightly different way too."
Including rhetorical assignment components	*Jessie, Wittig assignment interview:* "I never thought about it because we always think about organic chemistry in class and on paper. I never think of it as real people are using it to make real things, which I probably should… It was kind of cool seeing chemistry in this light, where more as like it's a product that's being bought and sold, and they needed to save money."
Providing clear expectations, support, and resources	*Gabriella, acid-base assignment interview:* "Maybe clarifying expectations with the calcium carbonate/citrate differentiations. That was something that I wasn't sure if I was supposed to do extensive research, and I decided to just kind of get some sort of an idea by looking at other publications... So specifying that it's something that we should be able to infer based off the structural information would probably have been helpful."
Engaging students in the peer review process	*Stephen, Wittig assignment interview:* "I think it's nice for an outside reader to say when something's confusing and ... and a lead on why so that I can work on making things easier to follow, because I do feel like when you're talking about electrons moving around in a reaction, it's easy to make something hard to follow probably. Those kinds of feedback were helpful."

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