Insights into Student Cognition: Creative Exercises as an Evaluation Tool in Undergraduate First-year Organic Chemistry

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Keywords: Open-ended, Student Artefacts, Meaningful Learning, Qualitative, Linking

Abstract

It is known that while students can be adept at recalling specific information, especially in end of semester summative exams, they can still often struggle to connect or link this information over different topic areas. In many cases, this issue is exacerbated by traditional assessments and teaching styles that focus on and reward students who have only interacted with the learning materials on a more surface level. Many attempts have been made over time to rectify this, with one such example shown in the use of Creative Exercises (CEs). CEs are open-ended tasks that allow students to connect as much prior knowledge as possible into one cohesive response, potentially developing a student's ability to link and connect disparate topic areas and content. In this study, CEs were introduced into a large scale first-year course and focused on fundamental organic chemistry reactions for the first time (to the best of our knowledge). Students performed the CEs in groups, and the paper responses were collected over six weeks (N=945 in total). Analysis of these artefacts revealed that students did indeed struggle to connect information over subsequent teaching weeks. This inability to connect information was despite being encouraged to do so both by the tasks and the teaching staff. Additionally, while more 'advanced' students (as noted by prior performance) were noted to raise more topics in a given week, they were just as susceptible to 'siloing' the information as lower-performing students. Recommendations are made on the future use of CEs.

Introduction

Historically, chemistry education within the higher education sector has been delivered through an 'expert dissemination' teaching style (termed by Ramsden, 2003, p. 115) as "teaching as telling" and by Trigwell, Prosser, and Ginns (2005, p. 352) as "information transmission/teacher-focused (ITTF)". One significant limitation to this approach is the potential to facilitate shallow or "surface" learning (Ramsden, 2003, p. 80). Ideally, it is intended that students engage in deeper learning throughout a degree, including skills in connecting and working with both discipline-specific and interdisciplinary knowledge. Many of our first-year students have come from schooling in which this type of teaching would have been the norm, resulting in their learning stalling at what Biggs and Collis' (1982) "Structure of the Observed Learning Outcome" (SOLO) taxonomy terms a "multistructural" stage. The multistructural stage describes when students, although having the ability to remember and understand discrete concepts, are unable to extend their understanding to the relational aspects of ideas, a higher-order skill that can lead to innovative thinking. According to Bloom's taxonomy, innovative thinking and creativity are also often regarded as advanced skills (Lasley, 2010, p. 108). While some students may be able to memorise some, or all, of the unit content, such rote learning is inadequate for achieving the learning objectives of the course and can result in poor performance in exams and through later years of study (Craik & Lockhart, 1972; Torun & Altun, 2014).

With traditional teaching methods inadequate to foster an interconnected understanding of chemistry as intended through the learning outcomes, there is an opportunity and an imperative to develop new approaches. To enhance student learning in first-year chemistry and beyond, we must find ways to assist students in drawing from a wide range of sources, including prior learning, chemistry-specific concepts, interdisciplinary perspectives, and life experience. Within the structure of our current degree programs, tutorials offer a productive site for our teaching innovation as an interactive and informal space where new approaches can be tried, evaluated, and adapted. The diversity of the group can become an asset.

The challenge then becomes one of elevating traditional teaching practices to allow students to achieve greater success and fulfilment in learning. Ausubel's assumptive learning theory is a framework that addresses what this could look like, advocating for students to engage in meaningful learning (Bretz, 2001). This theory describes a learning approach that fosters a linking of knowledge into a broad pool rather than discrete siloed content. The nature of learning activities and associated assessments dictates what sort of understanding is valued. Hence, these tasks that require exploration of broad topics to succeed will promote meaningful learning. In contrast, traditional approaches that do not test meaningful learning will push students away from changing their learning approach (Cooper & Stowe, 2018).

The design of an activity can be considered in terms of the responses they produce. Open-ended exercises have multiple acceptable answers and often provide less guiding information. In contrast, closed formats such as multiple-choice questions or algorithmic problem-solving scenarios have inflexible structure and can overestimate student understanding. (Lee, Liu, & Linn, 2011). Another dimension to learning activity design is how the answer is selected. Learner-centred exercises are those in which students play an active role in deciding what topics to use (Freeman et al., 2014). These assessments mirror students' cognition when undertaking meaningful learning as described by Ausubel, where they must consciously choose to link topics (Freeman et al., 2014).

Creative Exercises

Creative Exercises (CEs) combine both of these components, being an open-ended, learner-centred activity, historically introduced as an assessment format. Students are presented with an open situation and prompted to give as many correct, distinct and relevant statements as possible. It is worth noting that these exercises appear very similar in structure to 'mind mapping' or 'brainstorming' activities often utilised in teaching and learning (Buzan & Buzan, 2006; Finke, Ward, & Smith,1992) . However, Creative Exercises purposefully lack the structure of mind maps (which tend to incorporate boxes and linking arrows) and tend to be more past-focused (what do you recall/understand) rather than future focused (as is more the typical realm of brainstorming). CEs were first proposed by Trigwell and Sleet (1990) to address how traditional assessment questions did not accurately measure student understanding. Traditional assessment questions only tested factual and procedural knowledge, which could be answered with little real understanding of the concept. Trigwell identified two issues with traditional assessments – 1) They poorly assessed student understanding, and 2) their nature also discouraged meaningful learning, although only the first issue was explored in their study as they only used CEs as an assessment tool.

The second issue, whether CEs promoted meaningful learning, was investigated by Lewis, Shaw, and Freeman (2010) when they implemented multiple CEs within a semester-long course, as both homework assignments and in-class examinations. Ye and Lewis (2014) extended this study to a larger sample and specifically delved into how CEs could demonstrate linking of concepts by coding responses to specific and relevant subtopics to identify trends.

Gilewski, Mallory, Sandoval, Litvak and Ye (2019) further implemented CEs in a comparative study against traditional assessments such as multiple choice and short answer questions. They found that the groups attempting CEs achieved a higher average score than the control group on every exam compared (Gilewski et al., 2019). Student linking of chemistry concepts was also explored in greater detail, where links were quantitatively analysed and used to produce novel visual maps of related ideas.

To the best of our knowledge, the only example of CEs used outside of a purely chemistry context was when Warfa and Odowa (2015) examined junior undergraduate biochemistry students for links to prior chemistry knowledge. Previous iterations of CEs only examined fundamental first-year chemistry theory, so this study explored a new aspect of student understanding, the retention and linking of prior knowledge, which in this case was relating fundamental chemistry concepts to biochemical concepts being taught (Warfa & Odowa, 2015) .

The choice of implementing CEs into the tutorials is supported by previous studies that found evidence for validity when CEs were used in-class compared to being given as homework (Lewis et al., 2011). As an additional complexity, students can often be split into two to three streams (e.g. fundamentals, mainstream and advanced) based on prior chemistry performance in secondary school or alternative pathways. This streaming allows for an additional investigation into the suitability of CEs to students of different abilities.

Research Questions

This study aims to build upon the work that has been previously completed on CEs as a learning activity. Through this study, we have explored alternative topics to those previously studied (fundamental organic chemistry). Additionally, due to our tutorials' streamed nature, an opportunity was also present to investigate the suitability of CEs for students with different chemistry backgrounds and prior performance. To this end, this study sought to answer the following two research questions:

1) What do creative exercises as a learning activity reveal about how students link and connect fundamental-level organic chemistry?
2) How does a students' prior experience with chemistry influence their ability to link said concepts?

Methods

The following study was approved by the relevant Human Ethics committee of the host institution.

Theoretical Framework

This study used Constructivism as a framework to explore the effectiveness of CEs in this study. Constructivism describes learning as the act of incorporating new knowledge into existing knowledge and the subsequent interpretation of that knowledge (Bodner & Orgill, 2009). Hence, to learn, one must actively reconcile new information with previous experiences and either incorporate the new information, even perhaps changing one's beliefs, or undertake further testing of the new information through active inquiry.

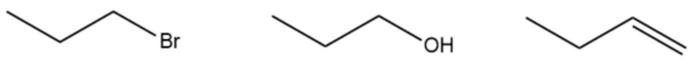
Regarding the CEs themselves, students can only respond to the open-ended prompts using whatever prior knowledge they had successfully stored in their long-term memory. The frequency that specific concepts were raised highlights which ones were prioritised or easily accessed within the student's cognition. Additionally, the 'accuracy' of student responses (i.e.

how often a raised concept was correct or not) was also considered. These incorrect beliefs, or misconceptions, are important to note as they can directly impede a students ability to incorporate new knowledge.

CE Design

Six CEs were written by two of the key researchers (Stephen George-Williams and Reyne Pullen) and attempted weekly by students in the organic chemistry section of a first-year semester-long course. Additional face validity was achieved through consultation with the other core teaching staff/lecturers, who were sent the exercises for comment each week before distribution. Organic chemistry theory can be grouped into fundamental concepts such as organic chemistry nomenclature, reaction schemes, electronic and steric effects, and spectroscopy. These concepts are relevant for understanding any functional group or reaction encountered at first- and even second-year chemistry. The nature of organic chemistry made it a good choice for studying student progression, as the same concepts would appear in multiple CEs throughout the semester and could be compared. Each CE provided three different organic compounds (Figure 1), changing each week, and asked students to provide as many "correct, distinct and relevant facts," in line with literature precedents (Figure 2) (Lewis et al., 2010).

Consider the following three molecules.



A B C

What can you say about them? List below anything your group can recall.
Think of as many correct, distinct and relevant facts as you can.

Figure 1. The CE implemented in Week 1, Semester 2 of 2019, demonstrating three distinctly different organic compounds.

Write down as many correct, distinct, and relevant facts you can about:

7.5 g of $CaBr_2$ is dissolved in a 1.50 L solution of excess Li_2CO_3 in the reaction

$$CaBr_2\,(aq) + Li_2CO_3\,(aq) \rightarrow CaCO_3 + LiBr$$

You'll receive 2 points for each statement. Seven statements will get you full credit for the problem.

Figure 2. Example CE from Lewis (2010) demonstrating the standard format of a typical Creative Exercise.

Data Collection

The university hosting this research is a member of the Group of Eight, which comprises Australia's largest and highest-ranking research universities. Its student cohort reflects this, with a wide range of cultural and educational backgrounds, including both domestic and international students. The standard of the first-year cohort can be considered as high-performing.

In first-year chemistry, three streams were available. Students who *did not* complete chemistry in their final secondary school studies are encouraged to undertake the fundamentals unit. Students who *did* complete chemistry in their secondary school studies are encouraged to undertake the mainstream unit, with high performing students further encouraged to enrol in the advanced unit. The prescribed syllabus was mostly similar between the units, with differences pointed out in the discussion where relevant. Note that students enrolled in these units have generally already completed a first-semester chemistry unit. A summary of these differences, alongside total student enrolments, can be seen in Table 1. Overall, 945 student artefacts were collected over the course of this study.

Table 1. Comparison between different streams in the second semester, first-year chemistry unit.

Stream	**Typical Characteristics**	***N***
Fundamentals	Had not studied chemistry at a senior secondary level	181
Mainstream	Studied chemistry at a senior secondary level.	426
Advanced	Excelled in high school chemistry, likely to major in chemistry.	95

The tutorials in which the CEs were utilised typically contain about 25-30 students alongside a single tutor. Students are provided with a tutorial sheet upon arrival, which contains many guiding questions designed to prompt the students on knowledge covered in the weekly lecture materials. In general, the tutorials utilise an active-learning peer-to-peer teaching style with students encouraged to complete the tutorial sheets together with guidance provide by the tutor only when required. Before undertaking the first CE, students were briefed on the premise that these CEs were formative exercises to assist in linking organic chemistry concepts covered during the course, with no assessment mark associated. Students were given 10 minutes and completed CEs in self-selected groups of 4-6 at the beginning of tutorials.

Coding Responses

A single researcher first analysed a small random selection of student artefacts (50). Notes were taken on which concepts were being raised by students and how often scientific errors were noted (i.e. the 'accuracy' of responses). NVivo12^{TM} was used to highlight specific areas of the student responses and were coded to sub-topic areas (e.g. functional groups identification, nomenclature or physical properties as seen in Figure 3) which were then collected to form broader topic areas.

This analysis was then shared with and moderated by the other two researchers and any discrepancies discussed as a group. This moderation was repeated until broad agreement was found for new randomly selected student artefacts. From this point on, the original researcher completed all future analysis until student responses from all six weeks had been coded.

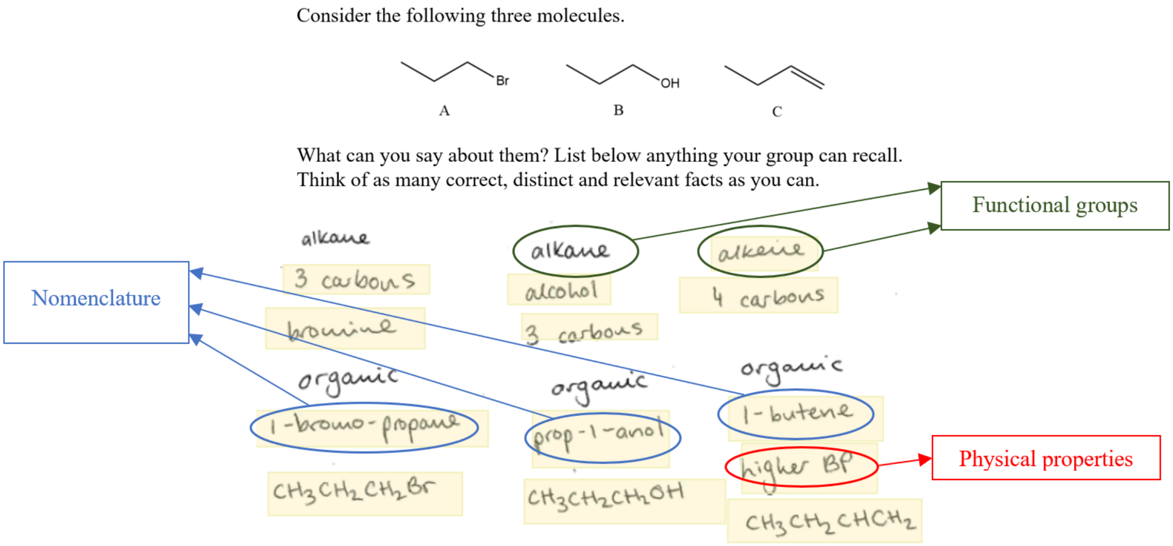


Figure 3. Example student response for week 1 CE with coding signified by highlights and some example sub-topic areas shown.

Limitations

This study was exploratory in nature, aiming to evaluate the potential of CEs in this institution for first-year chemistry. Other formal assessments were prioritised where relevant. For example, in week 5, students had an in-class quiz which occupied the majority of the tutorial time. Some tutorial groups did not attempt the CE for that week, so only four responses were collected from the advanced stream. These responses were disregarded in the subsequent analysis. Overall, the participation rates for the weekly CEs decreased over time.

Another limitation was the difficulty of standardisation. Tutorial sessions were numerous and ran asynchronously during the week, which meant that the researchers' direct supervision was impossible. Instead, instructions were provided to the postgraduate students supervising the tutorials on how to run the CEs. Because the postgraduate students were not very familiar with CEs, information such as the purpose of these exercises and feedback may have been interpreted differently by students in the study, potentially contributing to a hesitancy to engage. A hesitancy to engage was observed among some first-year students sitting the CEs, which would have affected the quality of the student artefacts collected. A factor that likely contributed to this was the absence of a formal assessment mark associated with completing the CEs during the semester or CEs in the unit's final assessment, unlike in previous studies (Ye & Lewis, 2014).

Results and Discussion

On inspection of the raw data, a shortlist of concepts was chosen for further analysis based on having a larger sample size of attempts (i.e. >20% of a given cohort raised a given concept over more than a single week). For these concepts, the frequency that students attempted to raise them and the 'accuracy' of these attempts was studied.

Distribution of Attempts

To account for each stream's different sizes (Table 1), the frequency of attempts was calculated as a percentage to compare between streams.

Naming Functional Groups and Structural Name

The most frequently raised concepts across all CEs was the identification of functional groups and the structural names for the provided compounds. The number of attempts to use these topics was high from the first CE, which can be thought of as reflective of students' prior knowledge. Students identified functional groups (Figure 4) more often than fully naming the structure (Figure 5), which was reasonable since identifying functional groups is usually the precursor to naming a compound.

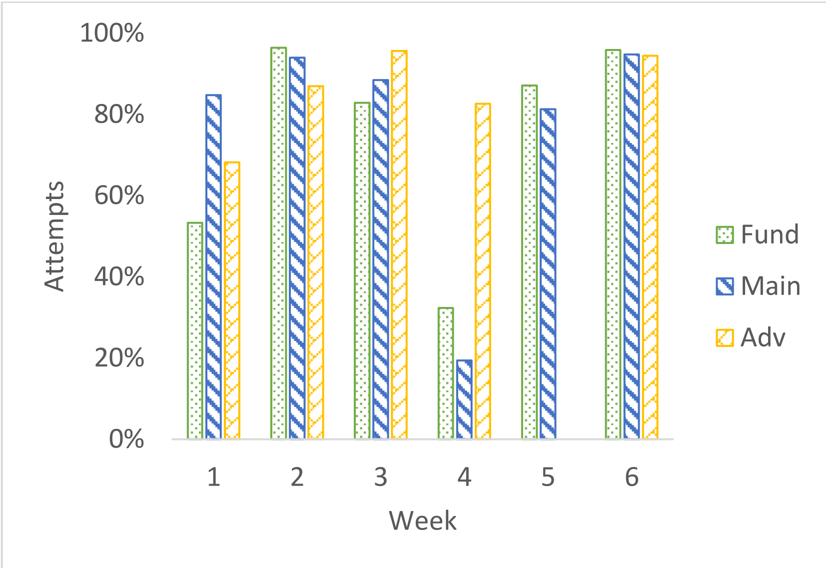


Figure 4. Percentage of student attempts to identify functional groups each week as per their enrolled stream (Fundamentals, Mainstream or Advanced).

Attempts to identify functional groups varied between weeks but stayed generally high, which could be linked to the relative ease of doing so. Attempts significantly decreased in week 4 (Figure 5) for the fundamentals and mainstream students, with the change being less pronounced in the advanced stream.

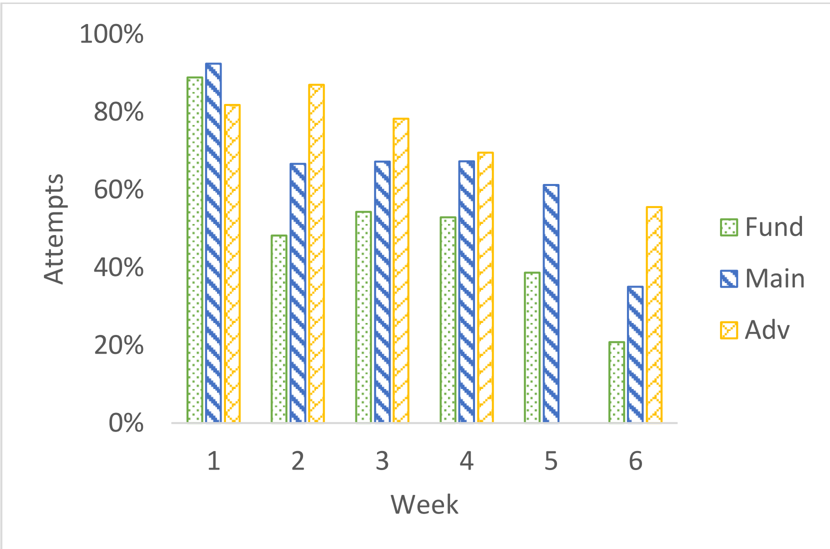


Figure 5. Percentage of student attempts to provide structural names each week as per their enrolled stream (Fundamentals, Mainstream or Advanced).

The proposed reason for these observations was that the week 4 CE contained haloalkanes that were not as regularly encountered as functional groups like alcohols, aldehydes, and ketones. Potentially, fundamentals and mainstream students did not learn or forgot about haloalkanes, while advanced students had better retention of more obscure prior knowledge. This type of analysis, where anomalies in the results are identified and linked to potential insights about student understanding, is one way we envision CEs can be used as an evaluation tool.

The fact that two similar concepts showed different distributions provided a promising avenue for future study. One such hypothesis is that a difficulty or effort threshold separated the two concepts, where naming functional groups was usually easy enough for students to always do it, with haloalkanes being the exception. Providing the full structural name, on the other hand, was either difficult enough or required enough effort to discourage students from attempting it as compounds became more complicated.

Spectroscopy

Functional groups and structural names are both concepts that can be grouped into an archetype where students already possessed prior knowledge and the content was reiterated throughout the course. Spectroscopy differs as it was introduced as a once-off set of lectures in weeks 2 and 3 for all streams. Hence, this concept's distribution of attempts gave insights into the immediate and delayed effects of this explicit instruction.

Before instruction in week 2-3, the lack of any mention (Figure 6) revealed that students either lacked prior knowledge about spectroscopy or had not linked it to organic chemistry. At the time of this study, spectroscopic identification of organic molecules did not form a significant component of the secondary school chemistry syllabus. In week 3, mainstream students used spectroscopy much more frequently than the other streams (Figure 6). This likely originated from the lecturers' different teaching style for each stream, where the mainstream lecture could have made very explicit connections between spectroscopy and organic chemistry, resulting in more responses when students were prompted in the CE.

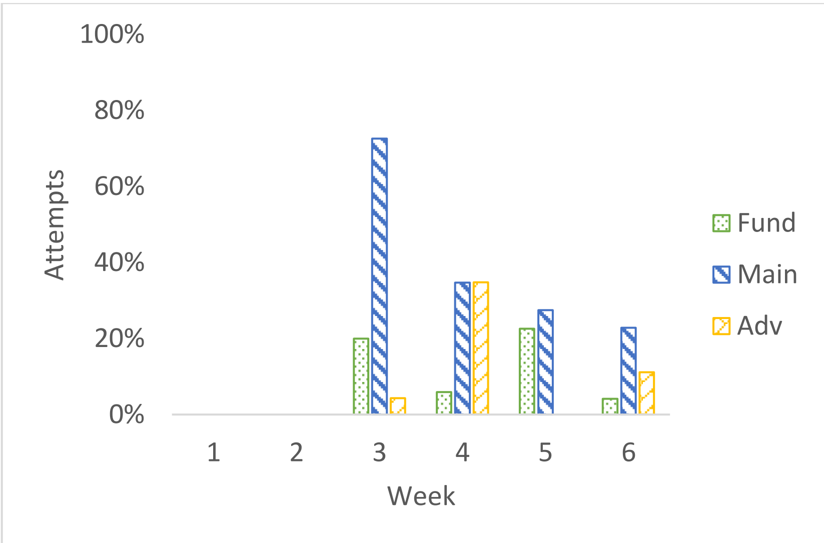


Figure 6. Percentage of student attempts to discuss any spectroscopy technique (mass, UV-vis, IR, NMR) each week as per their enrolled stream (Fundamentals, Mainstream or Advanced).

While the mainstream students' attempts to discuss spectroscopy decreased over time, the longer-term benefits were apparent since their attempt rates remained above the other streams. Fundamentals and advanced students continued to raise the concept, but less often and showed greater variation over the weeks.

Naming reactions and retrosynthetic analysis

Naming different types of reactions is a core concept that was repeatedly covered in lectures whenever new functional groups were introduced. Contrasted with nomenclature, however, these topics were less likely to be part of students' prior knowledge. These features likely influenced the distribution, with low initial attempts and a gradual improvement over time, as shown for naming relevant reactions (Figure 7). The fundamentals stream showed a clear increase in attempts in subsequent weeks (1-4), while the mainstream students also showed an overall improvement but were more variable.

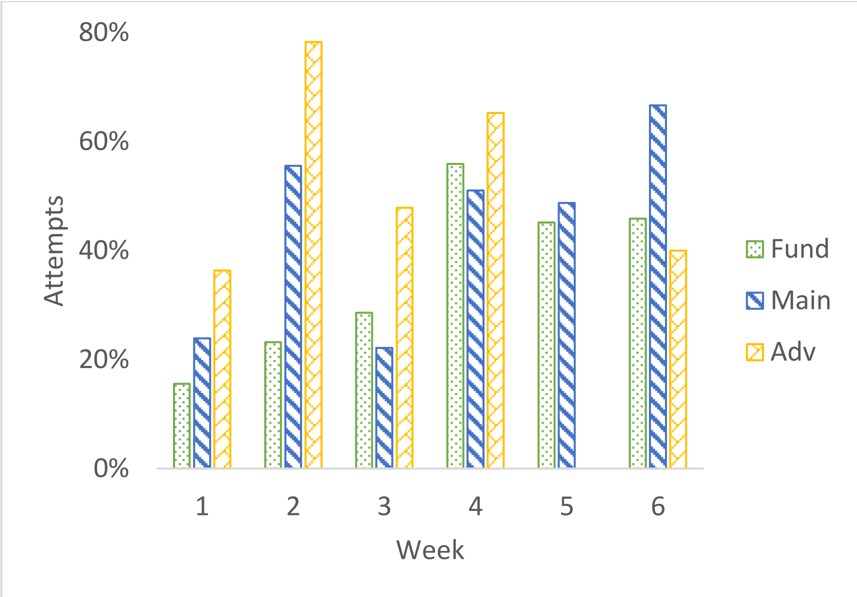


Figure 7. Percentage of student attempts to name relevant reactions each week as per their enrolled stream (Fundamentals, Mainstream or Advanced).

Naming reactions and providing additional reaction analysis can be treated as similar concepts at different levels of depth, supported by the distribution of attempts for reaction analysis replicating the features of low initial attempts and a gradual improvement over time (Figure 8). Reaction analysis can be considered a deeper or more complex concept. This consideration was supported by the fact that there was no example in any week or stream where students more frequently produced reaction schemes compared to naming reactions.

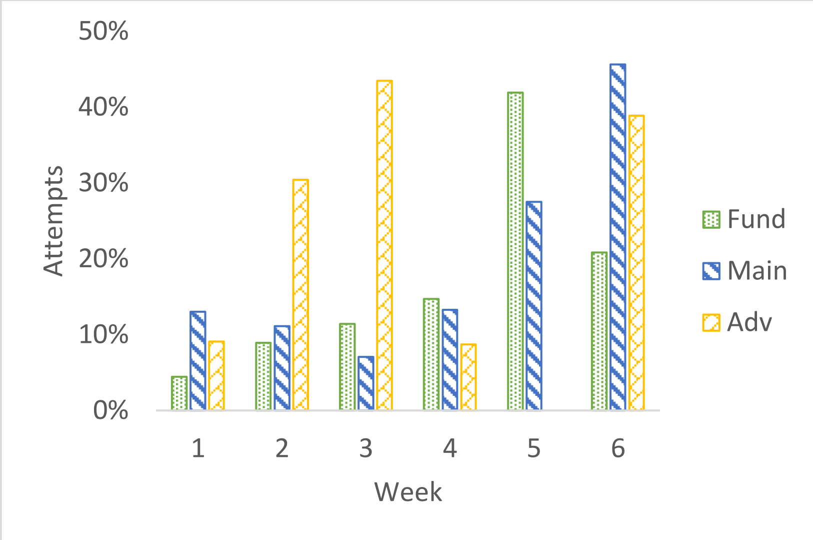


Figure 8. Percentage of student attempts to provide additional analysis regarding identified reactions (e.g. reaction conditions, product prediction or precursor reagents) each week as per their enrolled stream (Fundamentals, Mainstream or Advanced).

‘Accuracy’ of Attempts

The ‘accuracy’ of attempts was quantified by dividing the number of correct responses over the number of student attempts to raise a given concept. For example, if 100 students attempted to name a given molecule, but only 90 did so correctly, the ‘accuracy’ of attempts would be considered 90%. Two archetypes were observed for the ‘accuracy’ of responses, 1) High attempt rates with low ‘accuracy’ or 2) low attempt rates with low ‘accuracy’.

High attempt rates with low ‘accuracy’

For concepts like providing the structural name, the attempt rates were high, as shown in Figure 5, but were also accompanied by a decreased number of correct responses (Figure 9).

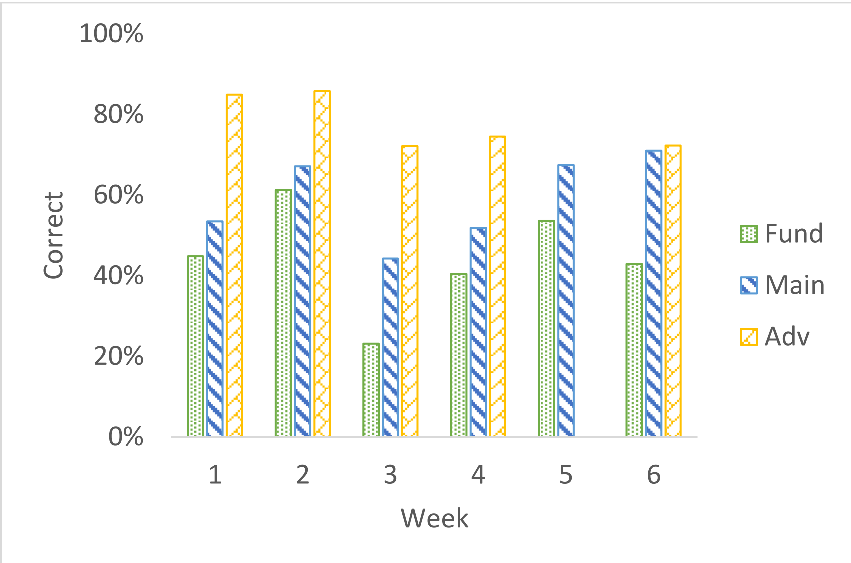


Figure 9. Percentage of student ‘accuracy’ of provided structural names each week as per their enrolled stream (Fundamentals, Mainstream or Advanced). Things that were considered incorrect included using the wrong name, incorrect, missing or unnecessary locant numbers, and incorrect punctuation (such as hyphens and commas).

Across each stream, the 'accuracy' of responses did not show a clear improvement over time. This lack of progress suggested that students were not fixing their naming errors, which was reasonable since nomenclature was not assessed in tutorials or quizzes, so students were unlikely to receive feedback on it. These results highlighted an area to focus on for intervention for common student misconceptions.

Combined with the distribution of attempts for the same concept, it was shown that advanced students named structures more often (Figure 5) *and* more accurately (Figure 9). This trend implies that even though the streams appeared similar when considering either 'accuracy' or attempt rate separately, they are more easily differentiated when both measures are combined. For example, advanced students attempted to name organic structures more often than other streams (Figure 5), and out of those attempts, they also achieved a higher 'accuracy' (Figure 9).

Low attempt rates with high 'accuracy'

In contrast, most other topics fell into a second group, which was described as having low attempt rates and low error rates or high 'accuracy'. All streams performed comparably here except in week 6. The concepts that best fit this distribution were often the ones considered more complex. It is believed that for these more complex concepts, students were not likely to attempt them unless they were confident about it, as it would be safer to use their time to talk about more straightforward concepts. Previous iterations of CEs (Ye & Lewis, 2014; Warfa & Odowa, 2015; Gilewski 2019) had explicit wording about how many statements would be required to score full marks, which certainly would have affected which concepts students mentioned.

Relating to the research questions

It is now of importance to consider this data with relation to the two research questions:

1) What do creative exercises as a learning activity reveal about how students link and connect fundamental-level organic chemistry?

The data discussed shows that students struggle to link fundamental organic chemistry concepts over time. While new concepts appeared in the students' responses as they progressed through the semester, they sometimes disappeared as additional new material was introduced. Furthermore, students showed a reluctance to raise new, more complex items but tended to be more 'accurate' when they did so. Overall, the CEs were powerful in being able to spot common student misconceptions *and* how little students were retaining or considering materials as the semester progressed.

2) How does a students' prior experience with chemistry influence their ability to link said concepts?

While it is true that advanced students were generally more likely to raise a wider berth of topics than the mainstream cohort (who in turn raised more than the fundamental students), there was still a surprising lack of linking occurring over the weeks. All students showed a tendency to shift their focus as the semester progressed, with new information appearing in the CEs only to be disregarded over time. As such, while more academically inclined students may perform better on a single task, there seems to be little to link the students' ability to consider the learning materials in a more holistic, connected manner.

Conclusion

Creative exercises, or CEs, are open-ended learning/assessment tasks that allow students to utilise a larger amount of prior knowledge in a less guided environment. Previous research had shown their potential in helping students link 'siloed' information, but further data was needed to investigate their use on a large scale and in the field of organic chemistry.

To meet this research need, a range of CEs, focused on introductory organic chemistry, were run weekly during tutorials at a large G8 Australian University in a first-year chemistry course (N=702). The CEs were run in groups of 4-5 students, were paper-based and tasked students with providing ALL information they could relate to three provided organic molecules. The written responses were collected, analysed and coded for thematic analysis.

One such analysis focused on specific concepts and how often the students raised them. Different distributions for certain topics were observed, such as structural names, which were frequently raised and gradually declined over time, and spectroscopy, which was not raised until it appeared later in lectures. These trends highlighted that students tended to focus on what they were comfortable with (or had encountered on numerous occasions) while avoiding new concepts they were still learning about and consolidating. Clearly, further encouragement to link to the newer concepts was required.

Another major analysis concerned the 'accuracy' of the statements made about certain topics, i.e. how often were the statements raised by the students scientifically correct? Interestingly, the most raised concepts were those that also contained the most common mistakes. Conversely, concepts that appeared less frequently (e.g. reaction types) were more likely to match current scientific theories. It would appear that while students were more comfortable raising previously encountered material, they were not necessarily correct in their thinking. If responded to promptly (e.g. during a given teaching semester), this data could highlight misconceptions with assumed knowledge that a teaching staff member may wish to address.

Given the insights into student understanding this exploratory study yielded, CEs are a promising evaluation tool in undergraduate chemistry. CEs may be good to assess student understanding, but a separate matter is whether the act of doing them will improve student understanding. This question would be an attractive future direction, which has been attempted by other researchers but not yet validated. Student interviews conducted by Lewis (2010) showed that students perceived an improved understanding from doing CEs, and Gilewski (2019) correlated CEs to improved final exam scores, though both of these can be considered as indirect measures of student understanding. As such, further investigation is still required.

Future Directions

While the next clear step in this research field would be to repeat the study, the COVID-19 pandemic prevented any face-to-face tutorials throughout 2020. As the current format of the Creative Exercises was paper-based and relied heavily on group communication, the authors felt that no such repeat study could be performed while remote tutorials remained a reality.

That being said and if face-to-face tutorials returned in full, there are many promising avenues to consider:

1) Scaffolding in early weeks (e.g. using specific guiding frameworks or questions) which is slowly pulled away in subsequent weeks.
2) Better 'marketing' to students and teaching staff to increase buy-in from all stakeholders. Could also be achieved with a faster response rate to student answers each week.
3) Having students take a picture of their own work to add to an electronic portfolio that they could access in every tutorial.
4) Piloting the same structure in other areas of chemistry, or indeed throughout other science discliplines.

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