Embedding metacognitive exercises in the curriculum to boost students' conceptual understanding

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Structured abstract

BACKGROUND

Engineers Australia asserts that professional engineers must exhibit technical competency, defining advanced engineering knowledge as being able to "comprehend and apply advanced theory-based understanding of engineering fundamentals to predict the effect of engineering activities." For engineering students in particular, metacognitive activity has been linked to their problem solving skills. Despite this link, operationalizing metacognitive activities in the curriculum to enhance problem solving has been difficult to materialise, and the few successful examples vary in scope and design.

PURPOSE

This paper extends prior investigations of a new curricular approach for embedding a metacognitive exercise in the curriculum that leads to students' greater conceptual understanding and evaluates the approach's potential to help students develop new capabilities for solving problems.

DESIGN/METHOD

The Structure of Observed Learning Outcomes (SOLO) taxonomy by Biggs and Collis (1982) was reconstituted as an in-class activity so students could recognise variations in structural complexity of various topics. Following the activity, students' justifications were analysed qualitatively to determine how the activity helped them recognise deficiencies in their own responses. Participating students were quantitatively compared to their non-participating peers on the subsequent summative assessment with respect to their 1) self-reported confidence, 2) performance, and 3) metacognition.

RESULTS

Nearly two-thirds of students justified their self-allocated, less-than-perfect mark by indicating their responses lacked depth. The activity showed students how their own answers were not yet fully developed and suggested how they could improve for the future, an essential aspect of formative assessment and feedback. Students also began to recognise that how diagrams are used in responses are more important than whether or not they are included in a response. Quantitative metrics on a subsequent, summative assessment showed significantly higher Cognitive Strategy and confidence measures as well as slightly higher performance for students who participated in the SOLO activity relative to their non-participating peers.

CONCLUSIONS

Paying attention to the characteristics of SOLO responses (e.g., using figures in multiple responses) presents an additional opportunity for helping students learn the important distinction between quantity versus structural complexity in their answers. By making such complexity visible to students, they will be more likely to enhance the complexity of their own responses when answering similar problems in the future. Evaluations of the adjusted SOLO activity presented in this paper demonstrate its potential to enhance students' awareness of their cognitive strategies when solving problems, which may ultimately promote students' confidence and problem solving abilities.

KEYWORDS

Metacognition; formative assessment; conceptual understanding

Introduction

Engineers Australia asserts that professional engineers must exhibit technical competency, defining advanced engineering knowledge as being able to "comprehend and apply advanced theory-based understanding of engineering fundamentals to predict the effect of engineering activities." Indeed, engineering professionals agree that problem solving is among the outcomes most important for being successful in the workforce (Passow, 2012). For engineering students in particular, metacognitive activity—or knowing about knowing (Flavell, 1976)—has been linked to their problem solving skills (Lawanto, 2010; Litzinger et al., 2010; Steif et al., 2010; Woods, 2000). Despite this link, operationalizing metacognitive activities in the curriculum to enhance problem solving skills has been difficult to materialise, and the few successful examples vary in both scope and design.

Koh et al. (2010), for example, investigated how different delivery modes affect students' metacognitive abilities and studied how pre-workshop experiences using simulation-based learning might improve students' metacognition. Other researchers have focused on metacognition-building activities that can be embedded within current course offerings. In a study of first-year chemical engineers, Ko and Hayes (1994) provided students with a problem solving framework that was followed throughout the semester so that students could be more deliberate and reflective as they worked through problems. Similarly, Hanson and Williams (2008) asked first- and second-year Statics students to write out explicitly the steps they followed to solve a problem so that students would be more likely to recognise what they do and do not know about different concepts. Results from each of these studies suggest that activities purposefully designed to help students develop their metacognitive capacitates allow students to become more self-aware and recognise gaps in their current knowledge.

As summarised by Meyer et al. (under review), research on metacognition tends to focus on how the development of metacognition can be introduced and integrated into the active student learning experience and to what effect. As Vos and de Graaff (2004, 543) argue, active learning in engineering is focussed '...on developing metacognition above or more than cognition'. In particular, Vos and de Graaf (2004) point to the capability of students to discern *structure* in given information as an important outcome of metacognitive development. The present study's authors developed a curricular mechanism for helping students discern levels of structural complexity in the understanding of concepts (Meyer et al., under review). Such an approach for embedding a metacognitive exercise in the curriculum sought to foster students' greater conceptual understanding, which in turn can open new capabilities for solving problems. The present paper extends that work by applying the approach to new concepts and tweaking the activity to address specific limitations as identified by Meyer et al. (under review). Moreover, it quantitatively evaluates the approach by comparing confidence, performance on assessment, and metacognition between students who engaged in the activity versus those who did not participate.

Curricular approach

The Structure of Observed Learning Outcomes (SOLO) taxonomy by Biggs and Collis (1982) was reconstituted as an in-class activity so students could recognise variations in structural complexity of various topics. This qualitative taxonomy was originally designed as an assessment device to help teachers categorise the structural complexity in students' answers to a question. The taxonomy distinguishes variation in terms of five categories according to the differences in structural complexity of answers. Biggs and Collis (1982) refer to the question as 'the cue' and the answer from a single student as either 'the datum' or 'data':

Prestructural: The cue and the datum are confused; that is, there is no indication of known relevant knowledge or relevant connection between the question and the answer.

Unistructural: Cue plus one relevant datum. The answer is only generalisable in terms of one relevant aspect connected to the question.

Multistructural: Cue plus isolated but relevant data. The answer contains several relevant aspects but, in terms of generalisability, these are conceptually independent.

Relational: Cue plus related and relevant data. The answer contains several conceptually related aspects that can be generalised within a given or experienced context.

Extended abstract: Cue plus related and relevant data plus hypotheses. Can generalise beyond the information contained in the question to other contexts.

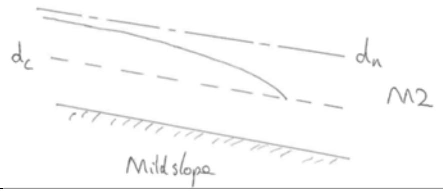
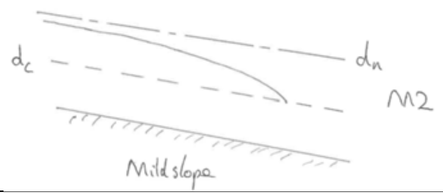
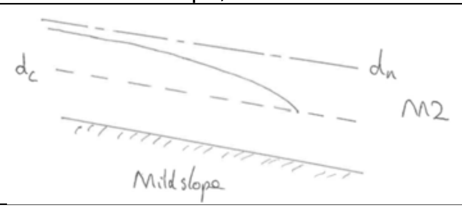
	Think of an M2 flow profile. Is the flow resistance (S_f) at a mid-point of the profile larger or smaller than that for normal flow? Say these are potential answers. What mark would you assign each?	
1	 The flow is approaching critical. Therefore E must be reducing, since E is minimum at critical conditions. $dE/ds=S_o-S_f$, and therefore $S_f > S_o$.	
2	Following the flow along an M2 curve, the depth is reducing, so the flow is accelerating (from continuity). Therefore the resistance must be less than if the velocity stayed the same (i.e. at uniform conditions). Therefore, $S_f < S_o$. Note that $S_f = S_o$ at uniform conditions.	
3	 At any point, the flow is accelerating. Therefore the resistance must be less than at normal (uniform) conditions and hence $S_f < S_o$.	
4	For an M2 curve, the depth reduces going downstream. The energy equation gives $dd/ds=(S_o- S_f)/(1-Fr^2)$. Since this is a subcritical flow with $Fr<1$, $(1-Fr^2)$ is positive. Hence, $S_f > S_o$ to give negative dd/ds. An M2 curve could also lead to a steeper (but still mild) slope. At the intersection of the M2 curve and the uniform flow on the steeper slope, $S_f = S_o$. On this steeper slope, S_o is now larger than before, and therefore S_f must have been larger than S_o on the milder slope, i.e. $S_f > S_o$.	
5	 For a wide channel, S_f varies as $1/d^3$ for constant q and friction factor. On an M2 curve, the depth is less than normal (see sketch), and therefore S_f is larger than for normal flow, i.e. $S_f > S_o$.	
6	 The flow has to "decelerate to reach" normal conditions. Therefore the flow resistance must be larger than at normal conditions (where $S_f = S_o$), hence $S_f > S_o$.	

Figure 1: SOLO activity for the concept of gradually varied flow

Meyer et al. (under review) investigated a departure from conventional applications of the SOLO taxonomy for assessment purposes *by teachers* and developed metacognitive assessment activity to be used *by students*. The authors conducted three trials of the activity with two cohorts of a civil engineering course (n=276 and n=264). Students were presented with several answers (varying in structural complexity) to a question about a concept in the course and asked to mark each response (as an example, see Figure 1). The teachers then showed students their marking schemes so that students could better understand what constitutes more and less advanced answers. Students' justifications for their marking schemes, their written reflections on the activity's usefulness, and the convergence of students' and teachers' marking schemes over subsequent trials suggest the activity supported deep forms of student learning.

Based on data from students from that prior research, the present study answers calls to make uniform specific aspects of answers to ensure that students focus on concepts as opposed to certain attributes of answers. For example, the present study provides purposefully incorrect discussions of diagrams or equations to ensure students understood the appropriate underlying mathematics as opposed to awarding marks based on the presence or absence of these features. In addition, this revised exercise pays attention to the length of answers so that more structurally complex answers are not readily apparent from an increased number of words on the page (Figure 1 is the revised exercise).

Data and methods

The present paper discusses evaluation of the fourth and final SOLO activity administered in a third-year open catchment hydraulics class (n=264), which focused on the topic of gradually varied flow. Previous SOLO exercises presented different concepts to students, including critical flow, the Froude number, and culverts. On the day of this fourth activity, 54 students turned in usable answers and agreed to participate in the study. These students are hereafter referred to as the "SOLO participants." Students were first provided the open-ended question related to gradually varied flow shown in Figure 1 and asked to write out their own answer. They were than presented with the answers varying in structural complexity, as shown, and asked to assign a mark ranging from 1–10 for each response (higher marks correspond to better answers). After marking the provided responses, students were asked to review their original answers and provide the mark that they believe it deserved in light of observing the variations in structural complexity in the provided responses. Students also were asked via an open-ended question to justify their own mark, and we report these qualitative data in this paper.

We evaluate this activity in several ways. First, we analyse qualitatively the responses from students justifying their marks to uncover how the activity may have helped students recognise some of the deficiencies in their own responses. We use standard content analysis (e.g., Lincoln & Guba, 1985) following an inductive, constant comparative method (e.g., Glaser & Strauss, 1967). Second, we compare students' marking schemes to the teacher's marking scheme to determine whether or not students systematically assigned higher marks to answers with graphs, for example, as opposed to thinking through the actual information presented in the graphs. Once the activity was complete, the teacher explained his marking scheme to the students as a form of immediate feedback so that students could understand why certain answers were better than others from his perspective. Third, we compare the SOLO Participants to the remainder of the class ("Non-Participants") on the subsequent summative assessment, which took place in the next class session and was attended by 229 students. This concept-based assessment used clickers to gather students' answers on exam-like questions related to gradually varied flow. We make comparisons between the two groups of students using independent samples *t*-tests on 1) a question related to their confidence in being able to answer the question, 2) performance on the test, and 3) a Cognitive Strategies construct (Table 1) that was asked with respect to the problems in the assessment.

This "Cognitive Strategy" construct is one of the five metacognitive constructs developed by engineering education researchers at the University of Washington in the United States. The complete suite of metacognitive constructs can be accessed at the following web address: [http://www.ee.washington.edu/research/dms/ee/researcher.html?id=href-metacognitive Constructs](http://www.ee.washington.edu/research/dms/ee/researcher.html?id=href-metacognitive). We report students' average scores across the five items shown in Table 1 to operationalize their Cognitive Strategy when completing the assessment. It is a measure of students' abilities to organise information, identify how the problem related to what was already known, use multiple techniques to answer a question, and plan an appropriate strategy for working through the problem.

Table 1: Items comprising the Cognitive Strategy construct[1]

I attempted to discover the main ideas in the question.
I asked myself how the question related to what I already knew.
I thought through the meaning of the question before I began to answer it.
I used multiple thinking techniques or strategies to answer the question.
I selected and organized relevant information to solve the question.

[1] 1: Strongly disagree; 2: Disagree; 3: Neither agree nor disagree; 4: Agree; 5: Strongly Agree

Results

After working through the problem and marking the series of provided responses, students marked their own responses and provided justifications. Many students justified why they awarded themselves marks as well as why they did not earn the full mark allocation. Nearly a quarter of students allocated themselves some marks because they included a diagram in their response (see Table 2). As noted in Meyer et al. (under review), previous renditions of the SOLO activity helped students realise the added benefit of including diagrams in responses, so it was encouraging to see this response. Similarly, previous SOLO activities helped students recognise the usefulness of mathematics in explaining answers, and nearly a fifth thought they deserved marks because they used equations in their explanations. Fewer students indicated that they deserved marks because they noted primary concepts in their responses, though this may have been implicit for the high percentage of students who responded explicitly that they left out a few details in their justification.

Table 2: Frequencies of students' justifications for their own marks following the SOLO activity

Comments Justifying Allocation of Marks	
Used a diagram	24.1%
Used mathematics	18.5%
Included primary conceptual ideas	16.7%
Straightforward response	13.0%
Answered the question in multiple ways	3.7%
Similar to one of the better provided responses	1.9%
Comments Justifying Reduction of Marks	
Poorly justified answer lacking depth with details missing	63.0%
Provided incorrect or irrelevant information	14.8%
Includes a poorly diagram but did not annotate or discuss well	9.3%
Includes incomplete mathematics	7.4%
Did not use a diagram	3.7%
Did not use mathematics	3.7%

Nearly two-thirds of students justified their self-allocation of a mark below 10 because their response was poorly justified, lacked depth, and had some details missing. Such a response was highly encouraging, as the SOLO activity sought to demonstrate to students how responses can vary in complexity. The activity showed students how their own answers were not yet fully developed and suggested how they could improve for the future, an essential aspect of formative assessment and feedback. As one student indicated, her answer showed "not a deep enough understanding." Another said his answer "only covers basic information with no real deep insight into the problem," one other noted that he "talked about one major topic whilst it was made clear there were at least two other topics to discuss," and a third said "I discovered the main ideas of the question but didn't have enough details." These reflections on the activity suggest that students began to recognise variations in structural complexity following the SOLO exercise, which was its main objective.

Unlike previous renditions of the exercise, the teacher included diagrams and equations in multiple provided responses to demonstrate to students that the *quality* of explanations related to those features were as important as their presence. Approximately 16% of students noted that they included graphs or equations in their responses but recognised that they did a poor job incorporating them into written explanations. One student noted that his answer "has a diagram but needs more annotations." Another said that his answer "had the correct diagram, but the conceptual understanding was lacking. Looking at [the teacher's] answers I realised I am being very vague and need to do a lot of studying." Thus, as SOLO activities are developed for new concepts or other classes, teachers should consider including diagrams and equations in multiple responses to help students recognise that *how* they are used are just as important as *whether* they are used. It is important to teach students not to expect to receive marks simply because they included a diagram.

To explore this idea further, we compared students' average marks for each question to the teacher's mark (Table 3). Generally, the order of quality in answers was consistent between students and the teacher. Questions 2 and 3 received the fewest marks by students on average as well as the teacher, though students' scores were higher than the teacher's. Perhaps this is additional indication that students believe they earn at least a few marks for including any information, no matter its relevance. Feeding back the teacher's lower marks to students for these questions may refute that belief. Students marked the other four questions lower than the teacher but in the right approximate order. Questions 1 and 6 fell in the middle of the marking scheme for each, and Questions 4 and 5 were at the high end for the teacher and students. Question 5, however, received an average mark of 5.85 from students and a 9 from the teacher. This response contained a diagram, but the number of words in the response was less than half the number of words in the response to Question 4. Perhaps students were hesitant to allocate more marks because of its shorter length. An implication of this is that teachers should make it explicit to students that the quantity of their responses is less important than the quality—concise answers can be more effective. Therefore, in combining these results, being purposeful about varying the length of responses and including diagrams in multiple responses in such SOLO activities can be used to help students with their learning.

Table 3: Comparisons between average class mark and the teacher's mark for each question

Question	Graph in Response	Words in Response	Class Mark	Teacher Mark	Difference in Marks
1	Yes	22	5.77	7	1.23
2	No	45	3.60	2	-1.60
3	Yes	22	3.90	3	-0.90
4	No	89	6.60	8	1.40
5	Yes	38	5.85	9	3.15
6	Yes	26	5.09	6	0.91

Finally, we compared SOLO-Participants to Non-Participants on the summative assessment administered in the subsequent class session. Students were asked to report on their confidence in being able to answer the questions, and the SOLO Participants were significantly ($p<.1$) more confident (average=2.52, where lower scores indicate greater confidence) than the Non-Participants (average=2.81) (Table 4). Trialling the activity across additional cohorts or classes of students would increase the sample size, which would likely yield statistical significance at a lower p-value. The finding is educationally significant in light of the summary argument presented subsequently. The finding is also consistent with prior research indicating that metacognitive activities promote students' self-confidence (e.g., Mani & Mazumder, 2013; Mazumder, 2012). For performance on the assessment, SOLO-Participants scored higher on average (5.38) than the Non-Participants (5.00) (Table 4).

Though this difference is not statistically significant, the direction of the difference is in the direction for which we would hope and expect following the administration of such a curricular activity. SOLO-Participants on average scored significantly (p<.05) higher (3.65) on the Cognitive Strategy construct than Non-Participants (3.40) (Table 4). This metacognition measure would be expected to be most strongly related to participation in the SOLO activity, which was indeed the case.

Combining these results, there is consistent evidence of a pattern of association between participation in this SOLO activity and greater metacognitive capacities among students, which in turn would theoretically be related to improved confidence and ultimately performance. A single educational intervention is unlikely to result in a major shift in students' metacognition and problem solving abilities, but the direction of the observed relationship is both encouraging and consistent with theoretical expectations. There is an unmistakeable resonance between the statistical data and students' qualitative reflections on the usefulness of this curricular activity.

Table 4: Independent samples *t*-tests comparing SOLO Participants to Non-Participants on summative assessment for 1) a question related to confidence, 2) performance on the assessment, and 3) score on a Cognitive Strategy scale.

	Student Group			
	SOLO Participants	Non-Participants	*t*	*df*
Confidence[1]	2.52	2.81	1.76*	206
	(1.03)	(0.97)		
	n=50	n=158		
Performance[2]	5.38	5.00	-1.14	227
	(2.27)	(2.13)		
	n=52	n=177		
Cognitive Strategy[3]	3.65	3.40	-2.26**	212
	(0.69)	(0.71)		
	n=51	n=163		

Note: **=p<.05, *=p<.10. Standard Deviations appear in parentheses below means.
[1] 1: No worries; 2: Fairly; 3: Perhaps; 4: Unlikely; 5: No way
[2] Scores are out of 11 possible points
[3] 1: Strongly disagree; 2: Disagree; 3: Neither agree nor disagree; 4: Agree; 5: Strongly Agree

Conclusion

This paper extends work by Meyer et al. (under review), which was an empirical investigation of how the SOLO taxonomy originally developed by Biggs and Collis (1982) can be adapted as a metacognitive learning activity for students. It improved that prior work by varying characteristics of responses (e.g., presence of diagrams in multiple SOLO responses) and providing a quantitative evaluation of the activity by comparing SOLO Participants to Non-Participants on the subsequent summative assessment. Varying characteristics of responses appeared to present an additional opportunity for helping students learn the important distinction between quantity versus quality in responses, and future SOLO designs should take this finding into consideration. Students' justifications for their marking schemes suggest that the activity helped them recognise the structural complexity in potential responses to a problem. By making complexity visible, students are more likely to enhance the complexity of their own responses when answering similar problems in the future.

Quantitative metrics on a subsequent, summative assessment showed significantly higher Cognitive Strategy and confidence measures as well as slightly higher performance for

SOLO Participants relative to the Non-Participants. Though the participants may have been more engaged in the class overall than their peers, both theory and previous research support the directionality of that finding. As such, and in combination with prior work by Meyer et al. (under review), our research supports the notion that reviewing course concepts using metacognitive activities that can be embedded into the curriculum—specifically the reconstituted SOLO activity—is a viable approach for making learning visible. Evaluations of the adjusted SOLO activity presented in this paper demonstrate its potential to enhance students' awareness of their cognitive strategies when solving problems, which may ultimately promote students' confidence and problem solving abilities.

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